The changing earth - new scientific challenges for ESA's living planet programme

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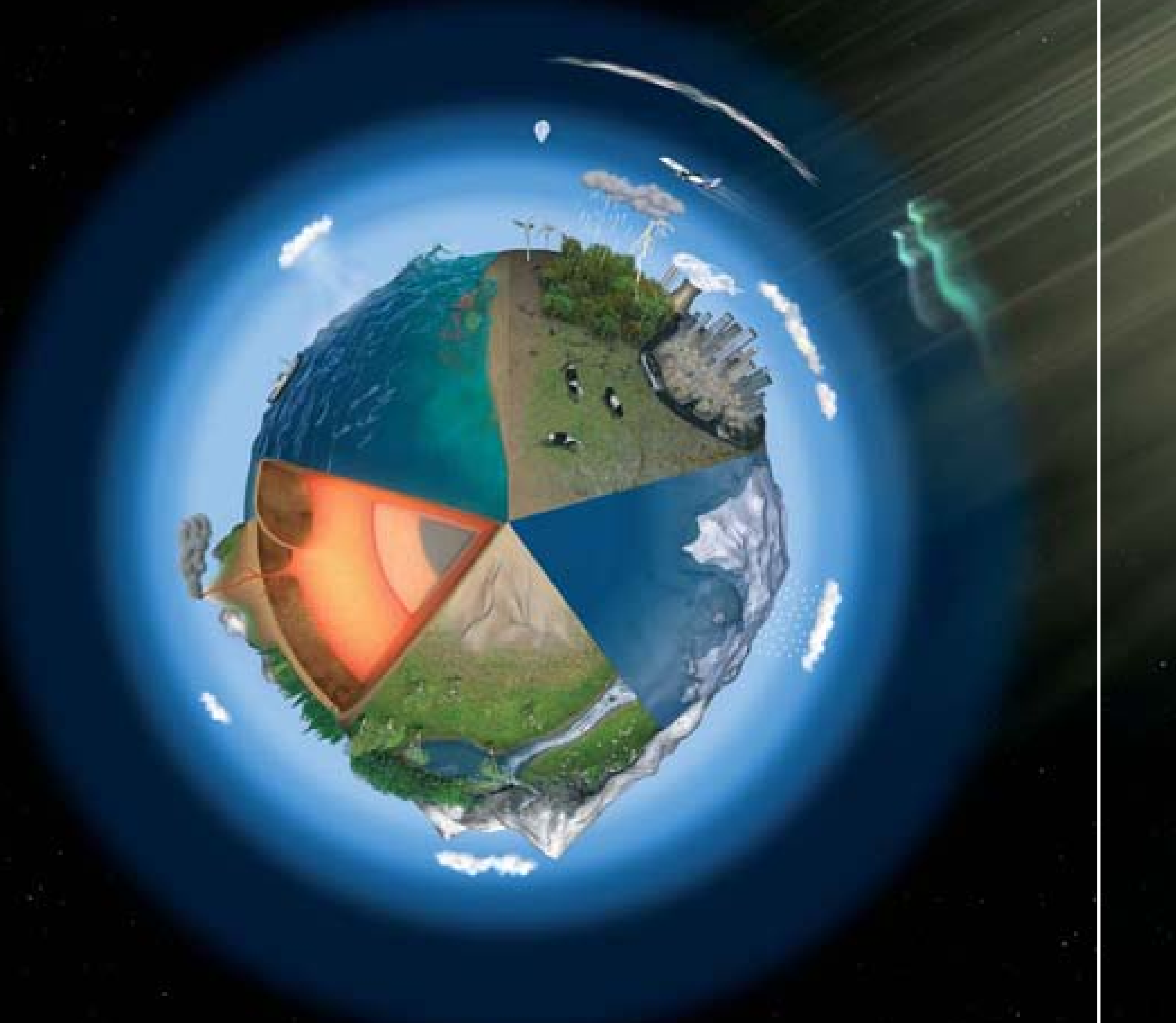
The Changing Earth



New Scientific Challenges for ESA's Living Planet Programme

European Space Agency
Agence spatiale européenne

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Foreword

Since the launch of ERS-1 some fifteen years ago, ESA has become a major provider of Earth-observation data to the Earth-science community. This has resulted in significant progress in a broad range of scientific areas, which also forms the basis for the development of new applications. This has been achieved mainly through exploitation of the ERS and Envisat satellites.

When ESA established its Living Planet Programme in the mid-1990s, a new approach to satellite observations for Earth science was initiated, with focussed missions defined, developed and operated in close cooperation with the scientific community. A comprehensive strategy was formulated for the implementation of the Programme, which has resulted in the selection of six Earth Explorer satellite missions covering a broad range of science issues.

At the Ministerial Council meeting in Berlin in December 2005, ESA Member States reconfirmed their commitment to the concept of the Living Planet Programme by funding the third phase covering the period 2008-2012. In addition to this, they approved the initiation of the Global Monitoring for Environment and Security (GMES) space component, in close cooperation with the European Commission. Although this programme is designed to provide data that underpin operational services, it will also contribute significantly to Earth science, in particular through the collection of long time series of observations. In turn, the Earth Explorers will provide new understanding that paves the way for new operational services: in this sense, the Living Planet Programme comprises complementary elements of research and operations. This synergy has long been demonstrated by the development and scientific exploitation of meteorological satellites, which continues to be an important part of the Living Planet Programme.

In order to make optimum use of its space assets, the Agency also implements a versatile ground segment together with associated user services that provide easy and uniform access to a wide variety of data sources. This is carried out in close cooperation with our Member States, ensuring that the most cost-effective implementation and optimum scientific return are achieved.

Development of specific cooperations with major science initiatives through, for example, the Earth Systems Science Partnership and with international user organisations such as the United Nations Conventions, have also been a feature of the Programme. In all its aspects, it has also been a major contributor to the development of European industry in the technology-development, manufacturing and service sectors.

The new scientific challenges outlined in this document have been formulated under the guidance of the Agency's Earth Science Advisory Committee and in consultation with the scientific community. These challenges will guide ESA's efforts in providing essential Earth-observation information to all relevant user communities, in close cooperation with our international partners.

Volker Liebig
ESA Director of Earth Observation

Contents

Executive Summary

Past records show that the Earth has always undergone major changes. The geometry of the Earth's orbit introduces regular changes in illumination conditions and thereby stimulates ice ages. Changes are a natural property of the Earth System, but there is mounting evidence that those that have been imposed on the Earth System during the last 150 years cannot be compared with any previous change. In the last century, humankind has driven the greenhouse-gas concentrations on Earth far beyond the maxima reached during the last 1 million years, has become responsible for 70% of the nitrogen and 95% of the phosphorus cycle on Earth, and has reduced tropical-forest areas by 50%. To determine whether these human-induced recent changes could ultimately de-stabilise the Earth System, both natural system variability and the consequences of human activities have to be fully understood and quantified. This represents the necessary scientific basis for sustainable future management of the Earth System as a whole.

The latter half of the twentieth century saw full emergence of the concept that the behaviour of planet Earth can only be understood in terms of the coupling between the dynamic processes in the atmosphere, the solid Earth, the hydrosphere, the cryosphere, the biosphere and the anthroposphere. All of these components are interlinked by a network of forcing and feedback mechanisms that affect the other components. Global-scale effects can arise from regional processes, and global-scale behaviour can have widely different regional manifestations. In addition, processes acting at one time scale can have consequences across a wide range of other time scales. This paradigm, in which the Earth is seen as a coupled set of dynamical systems, constitutes the scientific discipline known as 'Earth System Science'.

While the large-scale processes of global change are increasingly putting stress on the Earth's biosphere, other less wholesale changes may have equally serious consequences for the viability of ecosystems. Loss and fragmentation of habitat, forest degradation and loss of wetlands all remove the ecological niches occupied by species. Over-exploitation of the natural world, for example by over-fishing and over-grazing, will lead to loss of renewable resources and biodiversity. Still more stress, and even a health hazard, is placed on populations by water and air pollution, either through catastrophic events such as oil-spills and explosions of chemical plants, or more insidious effects from the long-term use of insecticides, run-off of nitrogen-based fertilisers, and air pollution in metropolitan areas. In addition to these threats to the natural world, managed systems are also subject to processes such as loss of fertility, desertification, water stress and erosion.

Two issues are at stake here. The first is **sustainability**. Human life draws heavily on resources provided by the living world: clean air, freshwater, food, clothing and building materials. In the interest of future generations, we have to find ways to guarantee that the functioning of the life-support system and the ability of the ecosystems to deliver goods and services are maintained. The second is **biodiversity**. On our own planet we are pursuing a course that is reducing the richness of life, and diminishing the World that we will hand on to future generations. The fact that life on Earth has existed continuously for several billion years is due to its diversity. It is very likely that in the course

The Challenges of the Oceans

Challenge 1: Quantify the interaction between variability in ocean dynamics, thermohaline circulation, sea level, and climate.

Challenge 2: Understand physical and bio-chemical air/sea interaction processes.

Challenge 3: Understand internal waves and the mesoscale in the ocean, its relevance for heat and energy transport and its influence on primary productivity.

Challenge 4: Quantify marine-ecosystem variability, and its natural and anthropogenic physical, biological and geochemical forcing.

Challenge 5: Understand land/ocean interactions in terms of natural and anthropogenic forcing.

Challenge 6: Provide reliable model- and data-based assessments and predictions of the past, present and future state of the ocean.

The Challenges of the Atmosphere

Challenge 1: Understand and quantify the natural variability and the human-induced changes in the Earth's climate system.

Challenge 2: Understand, model and forecast atmospheric composition and air quality on adequate temporal and spatial scales, using ground-based and satellite data.

Challenge 3: Better quantification of the physical processes determining the life cycle of aerosols and their interaction with clouds.

Challenge 4: Observe, monitor and understand the chemistry-dynamics coupling of the stratospheric and upper tropospheric circulations, and the apparent changes in these circulations.

Challenge 5: Contribute to sustainable development through interdisciplinary research on climate circulation patterns and extreme events.

The Challenges of the Cryosphere

Challenge 1: Quantify the distribution of sea-ice mass and freshwater equivalent, assess the sensitivity of sea ice to climate change, and understand thermodynamic and dynamic feedbacks to the ocean and atmosphere.

Challenge 2: Quantify the mass balance of grounded ice sheets, ice caps and glaciers, partition their relative contributions to global eustatic sea-level change, and understand their future sensitivity to climate change through dynamic processes.

Challenge 3: Understand the role of snow and glaciers in influencing the global water cycle and regional water resources, identify links to the atmosphere, and assess likely future trends.

Challenge 4: Quantify the influence of ice shelves, high-latitude river run-off and land ice melt on global thermohaline circulation, and understand the sensitivity of each of these fresh-water sources to future climate change.

Challenge 5: Quantify current changes taking place in permafrost and frozen-ground regimes, understand their feedback to other components of the climate system, and evaluate their sensitivity to future climate forcing.

The Challenges of the Land Surface

Challenge 1: Understand the role of terrestrial ecosystems and their interaction with other components of the Earth System for the exchange of water, carbon and energy, including the quantification of the ecological, atmospheric, chemical and anthropogenic processes that control these biochemical fluxes.

Challenge 2: Understand the interactions between biological diversity, climate variability and key ecosystem characteristics and processes, such as productivity, structure, nutrient cycling, water redistribution and vulnerability.

Challenge 3: Understand the pressure caused by anthropogenic dynamics on land surfaces (use of natural resources, and land-use and land-cover change) and their impact on the functioning of terrestrial ecosystems.

Challenge 4: Understand the effect of land-surface status on the terrestrial carbon cycle and its dynamics by quantifying their control and feedback mechanisms for determining future trends.

The Challenges of the Solid Earth

Challenge 1: Identification and quantification of physical signatures associated with volcanic and earthquake processes – from terrestrial and space-based observations.

Challenge 2: Improved knowledge of physical properties and geodynamic processes in the deep interior, and their relationship to Earth-surface changes.

Challenge 3: Improved understanding of mass transport and mass distribution in the other Earth System components, which will allow the separation of the individual contributions and a clearer picture of the signal due to solid-Earth processes.

Challenge 4: An extended understanding of core processes based on complementary sources of information and the impact of core processes on Earth System science.

Challenge 5: The role of magnetic-field changes in affecting the distribution of ionised particles in the atmosphere and their possible effects on climate.

of the present reduction of biodiversity, the Earth System's extraordinary stability in the face of external forcing is also being reduced.

Measurements of the Earth's properties provided by satellites are critical in providing access to many of the key elements of the Earth System. Four features of satellite measurements are particularly important in this context:

- They are **global**, enabling us to deal meaningfully with the overall properties of the system, whilst also providing observations of spatial heterogeneity.

- They are **repetitive and homogeneous**, so that time-varying phenomena can be discriminated. In many cases, long time-series are available, so that oscillations and trends can be recognised, and signatures of anthropogenic change can be distinguished from natural fluctuations.

- **Near-simultaneous** observations of many different variables can be made, allowing the state of the whole system to be diagnosed, and inter-relations within the system to be identified.

- **Near-real-time** data delivery (i.e. within a few hours) can be ensured, which facilitates assimilation of satellite data into complex models of the behaviour of the Earth System.

Our understanding of the Earth System is not a dry academic exercise; knowledge of the behaviour of our planet and the interactions between it and humanity (see the five accompanying panels) are fundamentally important in providing the basis for the management of our environment and our ability to derive sustainable benefit from it. At the same time as we begin to understand more deeply the Earth as a system, it has become clear that recent human activities are having a profound impact on this system, pushing it into states whose consequences for the planet and for humanity are currently unknown. An unequivocal indicator of this is the atmospheric carbon-dioxide concentration, which, since the Industrial Revolution and the mass use of fossil fuels, has risen far beyond its natural limits. Our understanding of CO_2 as a greenhouse gas, and the strong link between CO_2 concentration and temperature, both point to human activity leading to a warming World, unlike anything seen over at least the last million years. The complexity and inter-weaving of the Earth System's response to this human forcing has been clearly demonstrated by the measurements of atmospheric CO_2 performed at the Mauna Loa Observatory in Hawaii since 1958. The difference between estimated global emissions from fossil-fuel burning and the actual observed increase in the atmosphere has to be attributed to flows of carbon between the atmosphere and the Earth's land and oceans. It has been verified that on average the land and oceans together soak up roughly half of the emitted CO_2, and this 'sink' is increasing, but not keeping pace with emissions. Strong variations from year to year are symptoms of varying annual productivities of the land and ocean, with direct impacts on the resources (crops, forests and fish) available to humanity.

Global variations in the Earth System display very large regional differences. The human inputs to the system also show widely different patterns of change across the globe, be it deforestation, manipulation of hydrological resources, occurrence of fires, fossil-fuel burning, land-use management, etc. What seems clear is that these highly variable local and regional types of environmental management sum together to produce global changes with major influences on the Earth System. We are only just beginning to understand the related feedbacks and consequences for the Earth as a living planet, with humanity as one of its life-forms.

This document sets out the major challenges for our understanding of the Earth System, and in particular those areas where satellite data will make a major contribution. It provides the scientific direction for the future progress of the ESA Living Planet Programme.

1 Introduction

Since Earth Observation from space first became possible more than forty years ago, it has become central to monitoring and understanding how the dynamics of the Earth System work. The greatest progress has been in meteorology, where space-based observations have become indispensable, but it is also progressively penetrating many of the fields that make up the Earth sciences.

Exploiting Earth Observation from space presents major challenges to the researchers working in the Earth sciences, to the technologists who build the state-of-the-art sensors, and to the scientists interpreting the measurements made of processes occurring on or within the Earth's surface and in its atmosphere. The scientific community has shown considerable imagination in rising to these challenges, and in exploiting the latest technological developments to measure from space the complex processes that occur in the Earth System.

In parallel, there has been dramatic progress in developing computer models that represent the many processes that make up the Earth System, and the interactions and feedback between them. Success in developing this holistic view is inextricably linked to the data provided by Earth Observation systems. Satellite systems provide the fundamental, consistent, frequent and global measurements needed to drive, parameterise, test and improve those Earth System models.

These developments, together with changes in society's awareness of the need for information on a changing world, mean that it is now time to review how ESA can best focus its resources, and those of the European community that it serves, in order to address the critical issues in Earth System science.

While this strategy document is necessarily restricted to defining the scientific challenges and goals, it is a fact that many operational, managerial and regulatory activities essential to the safe exploitation of global resources, the conservation of sustainable ecosystems, and compliance with numerous international treaties and conventions, depend absolutely on the solution of the scientific problems set out here. There are established communities of applications specialists who can use the results of the scientific remote-sensing missions to maximise socio-economic and environmental benefits.

This document sets out a strategy whereby ESA can assess the most important Earth-science questions to be addressed in the years to come. It outlines the observational challenges that these raise, and the contribution that the Agency can make through its Living Planet Programme. While the document emphasises the scientific needs and objectives, the point of the strategy is to gather the appropriate space observations needed to carry out this science, and to harness the full capabilities of the Earth Observation Envelope Programme to do so. Hence, underpinning this strategy is a set of objectives for ESA's Living Planet Programme, which include:

- Launching a steady flow of missions addressing key issues in Earth System science.
- Providing an infrastructure allowing satellite data to be quickly and effectively exploited in Earth System science and applications.
- Providing a unique contribution to global Earth Observation capabilities, complementing satellites operated by other agencies and in-situ observing systems and fostering effective partnering with other space agencies to ensure the supply of important space data to European scientists.
- Providing an efficient and cost-effective process whereby science priorities can be rapidly translated into space missions, adequately resourced with associated ground support.
- Supporting the development of innovative approaches to instrumentation, and the use of space data to increase the scientific and technological strengths of, and space expertise within Europe.
- Contributing to educating the public, policy-makers and scientists regarding the gains to be made from the use of Earth Observation data in Earth System science, thereby ensuring the continual replenishment of scientific and technological excellence in Europe.
- Carrying out a strategic programme of scientific studies, technology development and campaigns, to ensure a full assessment of the science to be gained from space, reduction of the risk associated with new missions, and provision of the key tools needed to understand the information content from satellite sensors.

These challenges naturally place conditions on the ESA Member States, in that the ambitious programme to which Europe and Canada aspire needs sustained and adequate funding.

The overall vision for ESA's Earth Observation activities is:

……. to play a central role in developing the global capability to understand planet Earth, predict changes, and mitigate negative effects of global change on its population.

Current approved Explorer Missions of ESA's Living Planet Programme

2 Previous Strategy and Achievements

Since the launch of the ERS-1 satellite in 1991, and later ERS-2 and Envisat, the science community has had a unique and diverse data source for the development of its agenda. This has not only allowed significant scientific progress to be achieved, but has also enabled global cooperation, and has been the source of many new applications, some of which are already in operational use.

During the first half of the 1990s, ESA started to develop a new approach to Earth Observation. Previously, satellites had been either operational satellites for meteorology, or research satellites with numerous instruments that enabled a range of different, and often non-related investigations. According to the new approach, the scientific questions to be addressed should be the starting point for the definition of the satellite missions and should be the driver for all requirements to be fulfilled by the missions. This was the philosophy implemented in ESA's Living Planet Programme, whereby the Earth Explorers were to become the Earth-science missions.

The science and research element of the Living Planet Programme was laid out in the document ESA SP-1227 based on a description of the Earth System by four themes: the Earth's interior, the physical climate, the geosphere and biosphere, and the atmosphere and marine environment with particular emphasis on the anthropogenic impact. The strategy for the issues to be addressed was expressed in the form of candidate missions that were defined through consultation with the scientific community. These missions covered a broad range of issues in Earth science.

The programmatic implementation of the strategy was formulated in the Earth Observation Envelope Programme, which consists of the Earth Explorer component and the Development and Exploitation component. Satellite missions were divided into Core and Opportunity missions, where the former are larger missions and the latter smaller missions that are scientifically led by the proposing team. For both types of missions, the user-driven approach was a fundamental principle.

The selection of new Earth-science missions according to the new strategy started from the original list of nine missions, from which the GOCE and ADM/Aeolus missions were selected for implementation in 1999. For missions beyond these first two, Calls for Proposals were issued for both Opportunity and Core missions, later resulting in the selection of CryoSat, SMOS and Swarm as Opportunity missions, as well as EarthCARE as a Core mission.

The missions currently under implementation - all of them proposed by and developed in close cooperation with the scientific community - address a broad range of Earth-science issues. The strategy has thus given the Earth-science community a new and efficient tool for advancing our understanding of the Earth System. The scientific questions addressed also form the basis for the development of new applications of Earth Observation.


ATMOSPHERE
stratosphere
protective natural ozone layer
troposphere
HYDROSPHERE
CRYOSPHERE
GEOSPHERE
BIOSPHERE

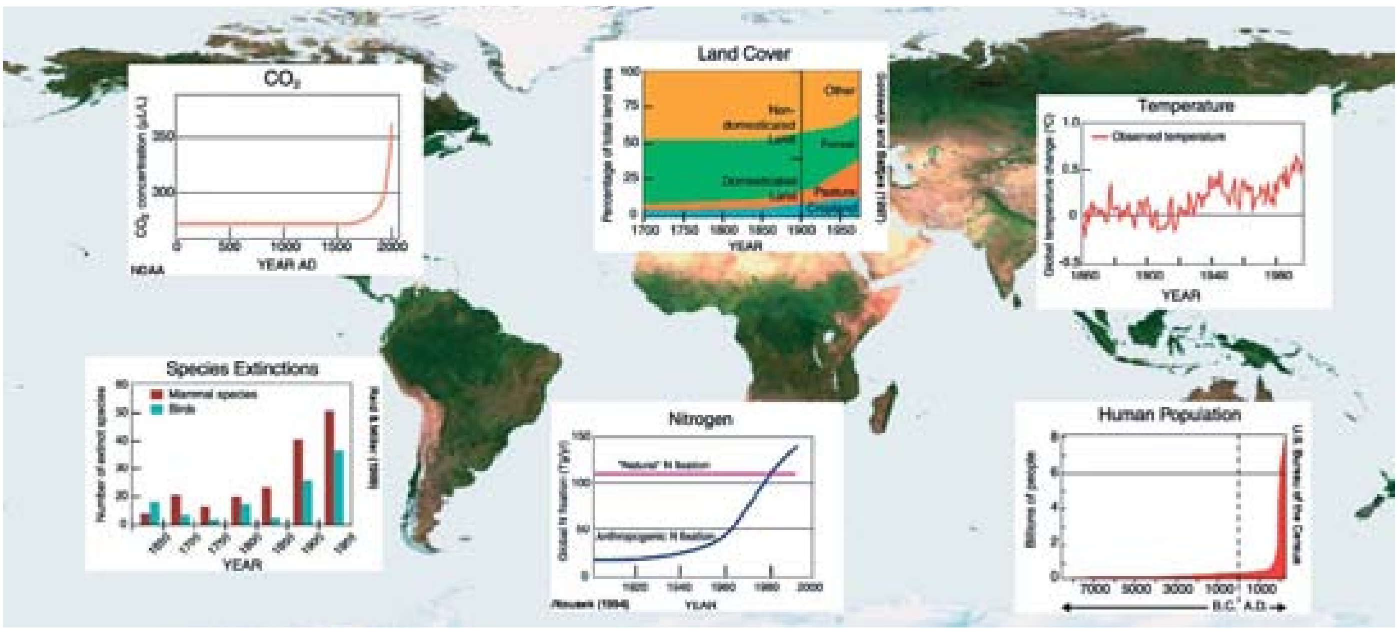
3 The Challenges of a Changing World

The most fundamental challenge facing humanity at the beginning of the 21st century is to respond effectively to the global changes that are putting increasing pressure on the environment and on human society. Three irrefutable and overlapping aspects of change need to be understood, managed and adapted to, namely:

- global change
- environmental degradation and sustainability
- growing human demand for resources, and societal vulnerability.

Global change deals with large- and small-scale processes that modify the Earth's atmosphere, land and ocean, and drive changes in the Earth System. Of particular importance is the growing interference of humankind. This interference, both on the global and regional scale, has greatly increased during the last century. One major element of global change is an increase in mean near-surface air temperature, largely driven by increasing emissions of greenhouse gases, such as carbon dioxide, methane, nitrous oxide and precursor gases of tropospheric ozone, into the atmosphere. This in turn drives a range of phenomena, such as the changes taking place in the Greenland ice-sheet, a rising sea level, reduced snow and sea-ice cover at northern latitudes, increased occurrence of fires and earlier greening up of vegetation. Many of these phenomena feed back into the climate system via modifications in albedo, biogeochemical cycles, ocean circulation, etc., leading to global and regional effects that are poorly understood and hard to predict with any confidence.

Climate variation, however, is only one aspect of global change. Other serious disturbances include large-scale manipulation of the land surface, e.g. tropical deforestation and the loss of biodiversity that goes with it, disruption of the hydrological cycle through excessive water extraction, and modification of atmospheric composition through emissions of pollutants. Another aspect of global change is the degradation of air quality in several parts of the World due to human activities. In all of these cases, human decisions about use of resources are leading to complex perturbations of the Earth System, with global consequences.



Selected aspects of Global Change, namely atmospheric composition, land cover, temperature, biodiversity, nitrogen fixation, and human population, based on information compiled by the International Geosphere-Biosphere Programme (IGBP).

Data Sources:
Carbon Dioxide: NOAA.
Land Cover: Goldewijk & Battjes, National Institute for Public Health and the Environment (RIVM), Netherlands, 1997.
Temperature: Source unspecified.
Species Extinction: Reid & Miller, World Resources Institute, Washington DC, 1989.
Nitrogen: Vitousek, 1994,
Human Population: US Bureau of the Census

Past records show that the Earth has always undergone major changes. The geometry of the Earth's orbit introduces regular changes in solar illumination conditions and thereby stimulates ice ages. Changes are a natural property of the Earth System, but there is mounting evidence that those that have been imposed on the Earth System during the last 150 years cannot be compared with any previous change. In the last century, humankind has driven the greenhouse-gas concentrations on Earth far beyond the maxima reached during the last 1 million years, has become responsible for 70% of the nitrogen and 95% of the phosphorus cycle on Earth, and has reduced tropical forest areas by 50%. To determine whether these human-induced recent changes could ultimately destabilise the Earth System, both the natural changes and system variability as well as the consequences of human activities have to be fully understood and quantified. This represents the necessary scientific basis for sustainable future management of the Earth System as a whole.

Dynamic processes in the Earth's interior also have a strong influence on climate, global change and natural hazards. Core convection is responsible for a major part the Earth's magnetic field and its variability. Mantle convection and plate tectonics are responsible for earthquakes, volcanic eruptions, landslides and tsunamis, with their resulting losses of human life and economic consequences. Even contemporary sea-level change is determined in small part by ongoing relaxation of the solid Earth following the last Ice Age.

Earthquakes and volcanic eruptions pose cataclysmic hazards to large centres of human population, and large explosive eruptions can also have significant climatic impact on a one- to ten-year time scale. Understanding their underlying causes is one of the grand scientific challenges of the solid-Earth investigations. Earth Observation from space is the only means of acquiring precise data on the deforming Earth on the scale of the phenomena themselves, and thus represents a central and indispensable tool for developing a physical understanding of these destructive phenomena and, ultimately, for mitigating their consequences.

Oil slicks from the stranded tanker 'Prestige' as seen by Envisat's ASAR intrument on 20 November 2002

An important challenge for space observations is to provide the ensemble of measurements needed to monitor the state of the Earth and how it is changing. However, an even greater challenge, in which space observations have a crucial part to play, is to build models that can predict how the whole atmosphere, ocean and land system will respond under the forcing that typically comes from human activities; to understand the feedbacks in this system, including those on the human population; and to provide measurements that can be used to drive, parameterise, enhance or be assimilated into those models.

Banda Aceh as seen by SPOT-5 before (2003) and after (30 December 2004) the devastating Indonesian tsunami. The damaged infrastructure and areas still under water are clearly visible.
Copyright: CNES and SpotImage, 2004. Processing SERTIT.

Environmental degradation and sustainability: While the large-scale processes of global change are increasingly putting stress on the Earth's biosphere (for example, many of the World's coral reefs are under threat as ocean water temperature and sea level rise), other less wholesale changes may have equally serious consequences for the viability of ecosystems. Loss and fragmentation of habitat, forest degradation and loss of wetlands even remove ecological niches occupied by species. Over-exploitation of the natural resources, for example by over-fishing and over-grazing, will lead to loss of renewable resources and biodiversity. Still more stress, and even a health hazard, is placed on populations by water and air pollution, either through catastrophic events such as oil-spill and explosions of chemical plants, or more insidious effects from the long-term use of insecticides, run-off of nitrogen-based fertilisers, and air pollution in metropolitan areas. In addition to these threats to the natural world, managed systems are also subject to processes such as loss of fertility, desertification, water stress and erosion.

Two issues are at stake here. The first is ***sustainability***. Human life draws heavily on resources provided by the living world: clean air, freshwater, food, clothing and building materials. In the interest of future generations, we have to find ways to guarantee that the functioning of the life-support system and the ability of the ecosystems to deliver goods and services are maintained. The second is ***biodiversity***. On our own planet we are pursuing a course that is reducing the richness of life, and diminishing what we will hand on to future generations. The fact that life on Earth has existed continuously for several billion years is due to its diversity. It is very likely that in the course of the present reduction of biodiversity, the Earth System's extraordinary stability in the face of external forcing is also being reduced.

The challenge this raises is partly observational, involving monitoring the status, health and productivity of the Earth's whole life-support system, including ecosystems, water bodies, soils, atmosphere and oceans, and identifying threats to them. The deeper challenge is to embed this information in global, regional and local environmental modelling and management systems.

Growing human demand for resources and societal vulnerability: A major driver of both global change and environmental degradation is humankind's ever-increasing demand for resources (energy, food, water, land). This only partly results from the growth in population, most of which is occurring in the developing world. Also important are the increasing demands per capita in both the developed and developing world, and particularly in such rapidly growing economies as China, Brazil and India. As a result, the current generation of physical and bio-geochemical Earth System models must evolve to include, as a central and increasingly important element, the role of humans as global actors.

This needs to be reflected in ESA's strategy, and has two facets. The first is the monitoring of humankind's impact on the planet, through urban spread, increased energy use and its consequences, changes in areas of managed land and management practices, increased exploitation of the oceans, etc. The second is to help understand, assess, predict and manage the robustness of human systems under global change and environmental stress. There seems little doubt that many communities and societies are becoming increasingly vulnerable to these changes. Examples include:

- Increased incidence of flooding due to sea-level rise, deforestation, increased human settlements in flood-prone areas and extreme weather conditions.

- Desertification.

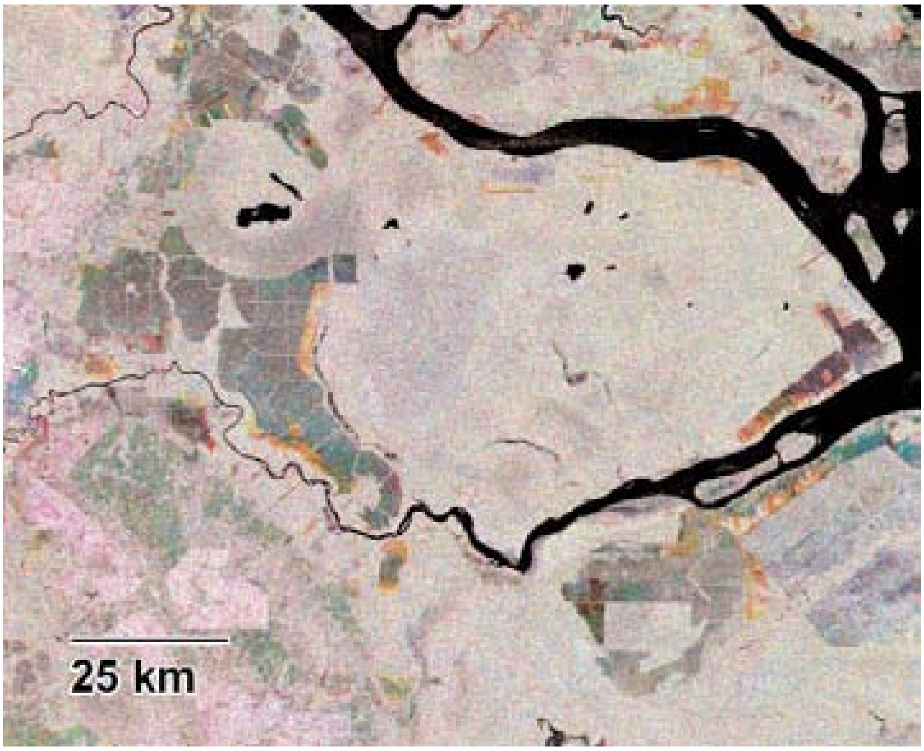
- Increased health risks, e.g. malaria, diseases related to air and water pollution, etc.

- Depletion of water resources, e.g. due to loss of glaciers in parts of central Asia where melt-water is the primary source of freshwater.

- Increasing population and vulnerable infrastructure in earthquake-prone regions.

The challenge here is to characterise the human element of the Earth System and its responses to changes and events in the system, with a view to managing societies in a manner compatible with the continued health of the planet.

It is against this backdrop of a changing world that ESA's science strategy needs to make an impact. The ubiquity of change, the interconnection between land, sea and atmospheric processes, and the scale and rapidity of change make space observations essential if we are to comprehend the whole picture and respond effectively to it. The scientific gains from addressing the challenges this raises will be further strengthened by their importance in international treaties.



Envisat radar composite image of the Kampar peninsula on Sumatra, Indonesia, revealing several large pulp and paper plantations (dark areas). The bright white spot in the centre far left of the image is the location of one of the largest pulp and paper mills in the World. Peat-swamp forest dominates the centre of the image (light shades of grey). Recent deforestation clearly shows up in both yellow and red. Rivers and sea channels are shown in black. On the right side of the circle-shaped forest patch, a road cuts through the remaining forest. Note the clearing alongside the road in the northern section close to the sea channel. In this raw ASAR Wide Swatch PRI composite, RGB channels relate to acquisitions on 8 February, 24 May and 2 August 2005. ASAR Wide Swatch Mode provides a pixel sampling of 75 metres.
Credit: SarVision, The Netherlands

4 Rationale of Earth System Science

The latter half of the twentieth century saw full emergence of the concept that the global-scale behaviour of the Earth can only be understood in terms of the coupling between the dynamic processes in the atmosphere, the solid Earth, the hydrosphere, the cryosphere, the biosphere and the anthroposphere. All of these components are interlinked by a network of forcing and feedback mechanisms that affect the other components. Global-scale effects can arise from regional processes, and global-scale behaviour can have widely different regional manifestations. In addition, processes acting at one time scale can have consequences across a wide range of other time scales. This paradigm, in which the Earth is seen as a coupled set of dynamical systems, constitutes the young scientific discipline known as 'Earth System Science'.

Several major scientific, technological, societal and political trends have provided a powerful impetus to this insight:

Scientific development and discoveries
Major progress in many Earth-science disciplines has revealed that traditionally separated disciplines, such as oceanography and atmospheric dynamics, are in fact intimately connected on a range of time and spatial scales. For example, the irregular El Niño Southern Oscillation (ENSO) phenomenon shows strong coupling of atmospheric and oceanic processes, which are in turn strongly connected to the spatial patterns and overall mean of global vegetation productivity. Spectacular new evidence from Antarctic ice cores has shown that, over long time scales driven by orbital fluctuations, the Earth's mean atmospheric temperature is intimately connected to the atmospheric composition, notably the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). It is very striking that, over a period of approximately 120 000 years, the atmospheric concentrations of

The Earth System

these trace gases lie naturally within well-defined bounds. Equally striking is the contrast between the slow transition of the Earth into the Ice Ages and its rapid emergence into the warm inter-glacial periods, in one of which we are fortunate to be currently living.

Woven into these cycles are processes occurring in the solid Earth. For example, the sea level in the Gulf of Bothnia is currently falling by about one centimetre per year due to the continuing rebound of the Earth's crust after melting of the Ice Age land ice. Global convection patterns of the solid Earth can cause huge devastation and enormous infrastructural damage, for example through earthquakes, volcanic eruptions, landslides and tsunamis. Volcanoes are also a major natural contributor to greenhouse gases. The eruption of Mount Pinatubo in June 1991 ejected tens of millions of tons of sulphur dioxide into the stratosphere, and is held primarily responsible for the global average drop in air temperature of about half a degree in 1992. Mount Etna is generally considered to be the largest localised source of natural carbon dioxide in the World, emitting several tens of thousands of tons per day, which corresponds to the CO_2 emission from a mid-sized city.

A primary lesson learned is that understanding the strongly nonlinear behaviour of the Earth System requires atmospheric, ocean, land, cryospheric and Earth-interior processes all to be considered, in addition to the external solar driver. The Earth needs to be thought of as a system that naturally regulates itself through a complex web of interactions and feedbacks between processes.

Humanity is part of the system

At the same time as we began to better understand the Earth as a system, it became clear that recent human activities are having a profound impact on this system, pushing it into states whose consequences for the planet and for humankind are unknown. An unequivocal indicator of this is the atmospheric CO_2 concentration, which, since the Industrial Revolution and the mass use of fossil fuels, has risen far beyond its natural limits. Our understanding of CO_2 as a greenhouse gas, and the strong link between CO_2 concentration and temperature, both point to human activity leading to a warming world, unlike anything seen over at least the last million years. The complexity and interweaving of the Earth System's response to this human forcing has been clearly demonstrated by the measurements of atmospheric CO_2 performed at the Mauna Loa Observatory in Hawaii since 1958. The difference between estimated global emissions from fossil-fuel burning and the actual observed increase in the atmosphere has to be attributed to flows of carbon between the atmosphere and the Earth's land and oceans. It has been verified that in most years the land and oceans together soak up roughly half of the emitted CO_2, and this 'sink' is on average increasing, but not keeping pace with emissions. However, there are large inter-annual variations in sink strength that are correlated with ENSO events, and in some years the Earth's surface acts as a net source. These variations are symptoms of varying annual productivities of the land and ocean, with direct impacts on the resources (crops, forests and fish) available to humanity.

Global variations in the Earth System display very large regional differences. The human inputs to the system also show widely different patterns of change across the globe, be it deforestation, manipulation of hydrological resources, occurrence of fires, fossil-fuel burning, land-use management, etc. What seems clear is that these highly variable local and regional types of environmental management sum together to produce global changes with major influences on the Earth System. We are only just beginning to understand the related feedbacks and consequences for the Earth as a living planet, with humankind as one of its life-forms.

Seeing the Earth from space

The psychological effect of first seeing the Earth from space, of seeing this haven of life hanging in the void, and being able to watch the ever-changing dynamics of this most interesting of all astronomical bodies, has been fundamental in turning the Earth System concept into a fascinating field of study and a quantitative science. Measurements of the Earth's properties provided by satellites are critical in providing access to many of the key elements of the Earth System. Four features of satellite measurements are particularly important for Earth System Science:

- They are **global**, enabling us to deal meaningfully with the overall properties of the system, whilst also providing observations of spatial pattern.

- They are **repetitive and homogeneous**, so that temporal patterns can be discriminated. Also important is that, in many cases, long time-series are available, so that oscillations and trends can be recognised, and signatures of anthropogenically caused change can be distinguished from natural fluctuations.

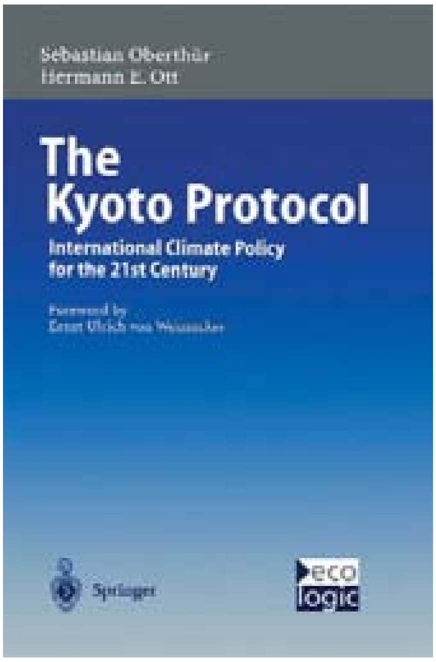
- **Near-simultaneous** observations of many different variables can be made, allowing the state of the whole system to be diagnosed, and inter-relations within the system to be identified.

- **Near-real-time** data delivery (i.e. within a few hours) facilitates data assimilation into forecasting models and improves forecasting skills. It allows optimizing of in-situ data sampling during field campaigns, and can be of fundamental importance for response and recovery operations in the context of crisis management.

The Earth System concept also allows us to understand how to fit the contributions from the different satellites together, and how to develop a global observing system best able to provide information on that system and its evolution.

Supercomputing, massive databases and model-data fusion

Our perception of the Earth as a system finds its scientific expression in a modelling spectrum running from the conceptual to the highly computational. These models encapsulate our understanding of the Earth's processes, their dynamic behaviour, their relations and their feedbacks. Quantitative models, by their very nature, consist of equations whose solution requires input data, and evaluating the models also requires data. Hence our total knowledge about the system is contained in our models, our measurements and how we put them together. Improved understanding of how to represent the dynamics of the Earth processes, together with the explosion in computing power, has allowed the construction of ever more powerful computer codes capable of solving the coupled equations making up an Earth System model with a spatial resolution of the order of ten kilometres. An equally influential development has been the explosion in the size of databases, both from models and satellite data, and the interconnectivity of computer systems and databases. Pinning these together has led to enormous advances in the methods of model-data fusion and data assimilation. These have been driven primarily by the needs of Numerical Weather Prediction, but the methods are cascading down to encompass all aspects of the Earth System.



Societal and political awareness

Everyone knows that recent times have seen changes to the Earth that can have a direct bearing on their lives. A major part of the human population lives in coastal areas, which are especially vulnerable as a consequence of sea-level rise, storm surges and tsunamis. An adequate level of protection in combination with an early-warning system is clearly desirable. It is also well-known that the ozone hole is a human-influenced phenomenon that increases the risk of skin cancer. We also know about large-scale deforestation, enormous fires a considerable part of which are manmade, increasing urbanisation, reduced water quantity and quality, loss of biodiversity, etc. There is, however, much more debate about climate change: its reality, how it is linked to some of the other phenomena mentioned above, whether recent weather extremes are symptoms of this change, and what will be the consequences for humankind and future generations. Politicians have responded to these concerns by formulating policies and negotiating treaties (e.g. Montreal and Kyoto Protocols). Improved understanding of the underlying science has been and will increasingly be crucial to such political initiatives on environmental issues of global concern. Here space has a critical role to play, within an Earth System context, by:

- Providing a means to weave incomplete, regional, fragmented ground observations, often scattered in time and space, into a synoptic global view, so that the connections and scale of events can be easily displayed to the public and policy-makers.

- Providing the data from which the interconnection of disparate processes can be demonstrated, and an effective management policy developed.

- Providing the monitoring capabilities needed for the assessment and enforcement of international treaties.

Earth System science and ESA's strategy

In summary, Earth System science provides the conceptual framework within which many environmental observations from space find their natural and most potent expression. None of the major Earth-science disciplines, when studied on a global scale and on differing time scales, can be isolated from any of the other disciplines. The deepest understanding comes from connecting process to process, to reconstruct the complex web that underlies the functioning of our planet Earth. In weaving this web, the relation of models to observations is crucial. Observations drive the understanding that leads to better models, and understanding drives observations allowing better model predictions.

This underpinning concept has very strong consequences for the ESA Earth Observation Science Strategy:

- ESA needs to develop satellite missions that have maximum impact on our understanding of Earth System behaviour, with an appreciation of where the key gaps are, and where other space agencies are contributing.

- In addition to providing satellite data, ESA must contribute to developing the infrastructure by which this investment can be effectively exploited in Earth System models.

- ESA must help to develop the expertise whereby satellite observations can be exploited in models.

Above all, ESA must be an active player in bringing together improved models with key data from satellites, and from the ground, in a framework in which these information sources can work together to greatest effect. From this process, we can derive our best estimates of the current state of our planet, and tentatively predict how it is going to evolve. This needs to be integrated with already ongoing efforts within IGOS, GMES, GEO and similar international undertakings.


HYDROSPHERE
condensation
vapour transport
precipitation
water vapour and
gas exchange
evaporation
wind stress
thermohaline
circulation
primary production
oxygen

4.1 Oceans

State of the art

Coupled models of the ocean, atmosphere and land are used to: project climate change for given scenarios, resulting from a range of CO_2 and aerosol forcing; predict inter-annual to decadal variability; provide seasonal forecasts and provide operational ocean forecasts on time scales of days to weeks, including extreme events such as storm surges and harmful algal blooms. These models require routine access to observations that characterise the three-dimensional state of the ocean.

During the last 15 years, satellite observations have become a fundamental data source in characterising ocean processes acting on global, regional and local scales. For example, mid-latitude global observation of ocean mesoscale structure has allowed us to acquire a new quantitative understanding of the mean and eddy kinetic energy of the ocean circulation and associated transport of heat and mass. However, in contrast polar mesoscale features, the presence and dissipation of internal waves, semi-diurnal and other high-frequency processes acting in shelf seas and in coastal and estuarine environments are not yet sufficiently well-resolved by satellite observations. Hence, our ability to quantify exchange processes between the coastal-shelf seas and the open ocean is presently limited.

Air/sea interaction and land/ocean exchange processes are very complex and act over a wide range of spatial and temporal scales. Physical processes include exchanges of momentum, heat, and water, while bio-geochemical processes involve shortwave-radiation penetration and absorption, and the exchange of gases, aerosols and other natural or manmade chemicals. The full complexity of many of these processes remains to be captured in state-of-the-art coupled models. Combinations of existing and new global data sets are thus needed to address the remaining deficiencies, to fill the knowledge gaps, and to reduce uncertainties in predictive and scenario calculations.

An understanding of the coupling between physics and biology, and in particular climate and bio-geochemistry, is essential for the future development of knowledge-based marine ecosystem management. Since marine ecosystems are strongly nonlinear, small-scale perturbations can cascade to larger scales and ultimately affect the global ecosystem structure. Feedback mechanisms are only partially understood regarding the influence of marine biology on climate, such as the effect of phytoplankton communities on heat penetration into the upper ocean, the biological contribution to CO_2 uptake and its exchange between ocean and atmosphere.

Coastal systems are experiencing unprecedented changes and are becoming more susceptible to natural hazards, more costly to live in, and less able to sustain the marine ecosystem. A broad spectrum of phenomena, from global warming and sea-level rise, declines in fish catches, seasonal oxygen depletion, episodic harmful algal blooms and loss of biodiversity are exhibiting troubling trends in their magnitude and frequency in many coastal areas. These changes reflect the sensitivity of coastal ecosystems to both the nature and the dynamics of the external physical forcing that impinges on them directly, or indirectly, via the propagation of variability on basin- to coastal scales. Moreover, anthropogenic nutrient and freshwater inputs, the question of ‘trans-boundary’ currents and the quantities of material transported are all of major concern, and still practically unexplored in terms of satellite observations.

Challenges

Despite significant advances in our understanding of the Earth System from the use of observations, models and their combination via data assimilation, there are still knowledge gaps regarding ocean variability and dynamics on temporal and spatial scales ranging from days to centuries and local to global. These gaps include:

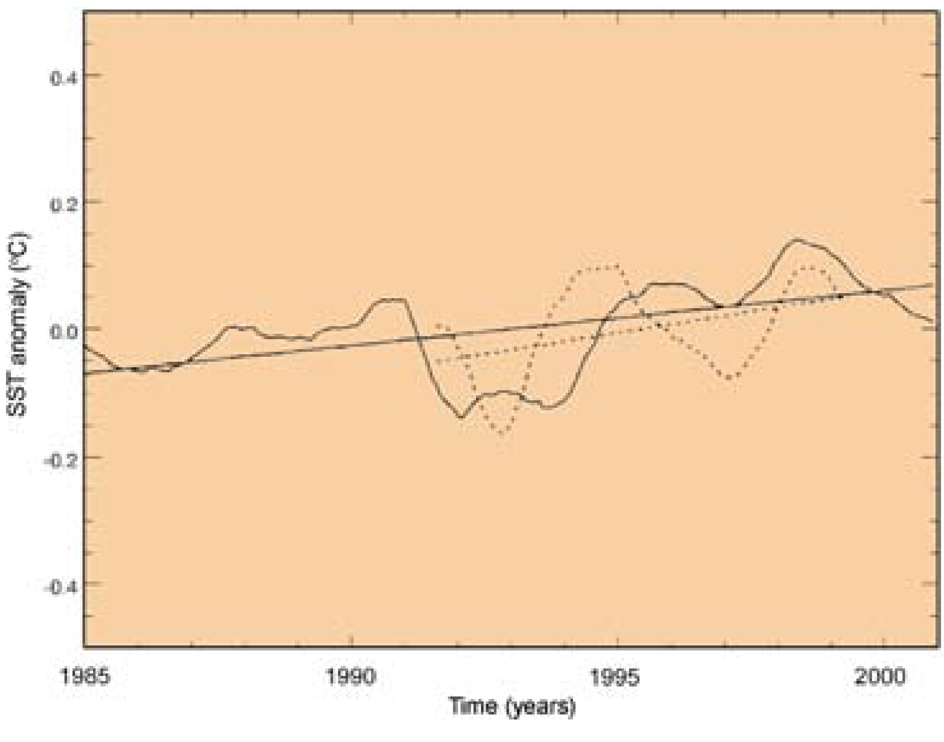
- The role of the oceans in human-induced climate change and its interaction with natural variability and change, e.g. salinity, global thermohaline circulation variability, presence of Rossby waves and internal waves, poleward transport of heat and basin exchanges.

- Atmosphere/ocean interactions, e.g. gas and heat exchange, aerosol input and output, cloud formation, and net fluxes of momentum, freshwater, and radiation.

- Land/ocean interactions, e.g. sea-level change, erosion, run-off, contaminant and nutrient loading.

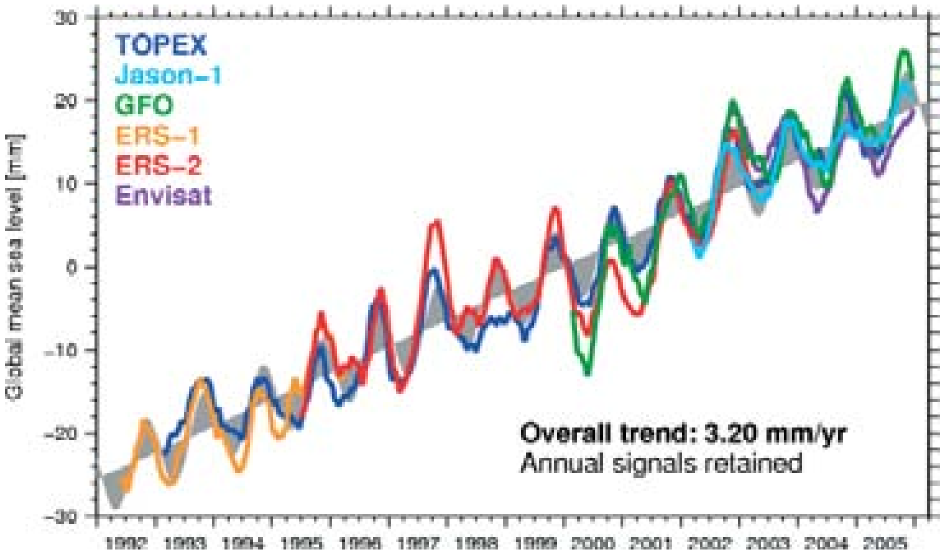
- Internal waves and mesoscale variability and eddy shedding, their relevance for heat and energy transport and influence on primary productivity.

- Marine ecosystem functioning and coupling between physical and bio-geochemical processes, e.g. oxygen and nutrient fluxes, CO_2 uptake and transport, including the influence of the biological pump.



Globally averaged sea-surface-temperature anomalies, after removal of annual cycle and El Niño, from space-based AVHRR (solid line) and ATSR (dashed line) instruments. The trends are 0.09 and 0.13˚C per decade, respectively.

Credit: AGU; Lawrence et al., JGR, Vol. 109, C08017, 2004



Global sea-level rise derived from satellite altimeters over the period 1992-2005.
Credit: R. Scharroo, NOAA

- Optimal integration of satellite and in-situ data into models, to advance understanding of physical and bio-geochemical processes and their coupling, and to assess the state of the global ocean and marine carbon system.

The climate-prediction problem is aggravated by the existence of several unresolved scientific problems, such as the effects of water-mass variability on the vertical stratification, the coupling between wind-driven gyres and thermohaline circulation, and the connection between tropical and extra-tropical disturbances on seasonal to decadal time scales. Moreover, the impact of climate change on ecosystem variability and dynamics is still largely unpredictable.

Biochemical cycles and oceanic food chains depend on exchanges of gases and particles at the air/sea interface in a manner that is almost unknown. For instance, measurements of fluxes of oxygen and other substances at the air/sea interface are extremely rare, and require specialised, synergetic sensing techniques. A multidisciplinary, integrated approach is a prerequisite for addressing these challenges.

The Challenges of the Oceans

Challenge 1: Quantify the interaction between variability in ocean dynamics, thermohaline circulation, sea level, and climate.

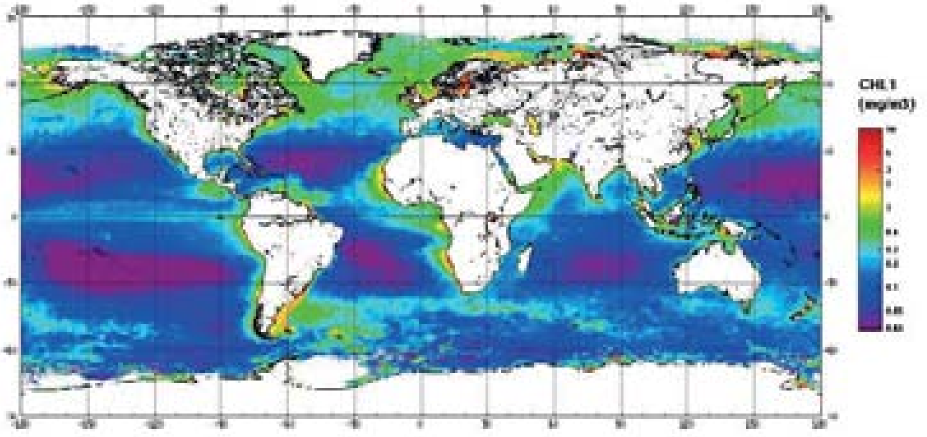
Challenge 2: Understand physical and bio-chemical air/sea interaction processes.

Challenge 3: Understand internal waves and the mesoscale in the ocean, its relevance for heat and energy transport and its influence on primary productivity.

Challenge 4: Quantify marine-ecosystem variability, and its natural and anthropogenic physical, biological and geochemical forcing.

Challenge 5: Understand land/ocean interactions in terms of natural and anthropogenic forcing.

Challenge 6: Provide reliable model- and data-based assessments and predictions of the past, present and future state of the ocean.



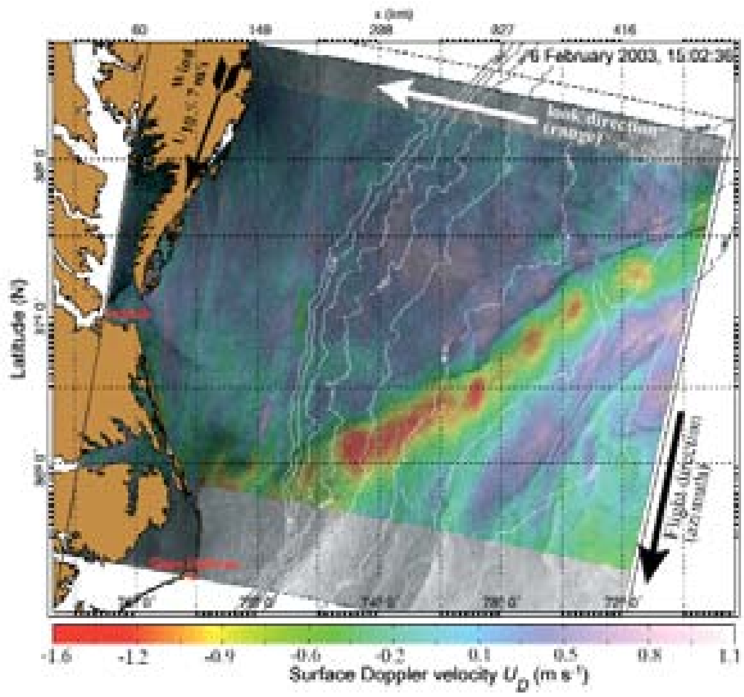
Mean annual distribution of chlorophyll-a in ocean waters in 2003, from Envisat MERIS data.
Credit: ESA

Observations

The systematic, long-term joint provision of satellite and in-situ gathered data, and their integration into appropriate models of the Earth System are of paramount importance for understanding ocean variability and dynamics. Moreover, satellite data are well-suited to support routine monitoring and global predictions of the state of the marine environment and the climate. Thus satellite remote sensing with global coverage has become essential to observe and understand physical and bio-geochemical processes that occur in the upper ocean. However, a comprehensive and integrated observing system, expanded with new satellite-observation capabilities in conjunction with in-situ systems, must be developed and sustained in order to address the challenges.

Integrated, optical and all-weather microwave-sensor (active and passive) data sets need to be sustained and to be complemented by new measurement techniques. In order to capture the mesoscale variability of the ocean at the global scale, alternative swath altimetric techniques will be needed if the continued availability of three simultaneous conventional altimeters is not assured. Moreover, we presently have no unified method with which to consistently quantify wind, waves, and surface currents and their interactions. This calls for synthetic- aperture, interferometric and Doppler centroid radar techniques, complemented by altimetry and the exploitation of signals of opportunity from Global Navigation Satellite Systems (GNSS).

Biological and ecosystem modelling requires the quantification of chemical variables such as nutrients, oxygen, and CO_2, which are not so far measured by remote-sensing techniques. This lack of measurements imposes major constraints on model development and validation.



Envisat wide-swath SAR backscatter image of the ocean surface off Cape Hatteras, USA, indicating radar cross-section (grey shades) and surface velocity (colours). Oceanic fronts appear as sharp gradients in backscatter, while the structure of the surface velocity is related to the Gulf Stream's separation from the coast.
Credit: Ifremer & AGU; Chapron, Collard & Ardhuin (2005), J. Geophys. Res., 110, C07008, doi:10.1029/2004JC002809

To obtain a measure of rapid changes in sea-surface temperature, their influence on air/sea interaction, and biogeochemical processes in the upper ocean on diurnal time scales, a precise, global, high-resolution microwave sea-surface temperature measurement capability needs to be developed. Multi-channel optical and microwave techniques should also be maintained and further explored on geostationary satellite platforms to capture high-frequency, daily to sub-daily variations at synoptic scale. In particular, this is needed for ocean-colour applications in coastal and shelf seas, where processes are strongly influenced by tidal dynamics and cross-shelf exchanges with the open ocean.

To successfully resolve 3D processes in the ocean, the satellite observations need to be adequately combined with data from long-term moored buoys, profiling floats, autonomous underwater vehicles, acoustic tomography and conventional and voluntary ship-borne observations. In the future, more routine use of Observing System Simulation Experiments via data assimilation would facilitate optimisation of these observing-system elements. Moreover, by 2020 global models are expected to have a spatial resolution of better than ten kilometres and will therefore have a major need for data to match.

System approach
Knowledge of the interaction between the Earth System elements is a prerequisite for understanding how the processes in one element of the Earth System influence the others over long distances. A marine system approach involves both observations and modelling of the coupled physical and biochemical processes in the open ocean and coastal areas. The marine system is strongly influenced by, as well as interacting with, the other elements of the Earth System.

Many of the challenges associated with air/sea interaction processes rely on proper observations and understanding of the state of the atmospheric and oceanic boundary layers, and the corresponding fluxes across the ocean/atmosphere interface. This work will also benefit significantly from accurate quantitative knowledge of sea-surface roughness on cm to km scales. Moreover, the importance of the hydrological cycle for the upper ocean can only be fully appreciated by quantifying the processes (evaporation, precipitation, run-off) that govern the ocean's interaction with the atmosphere, cryosphere, and land surface.

The physical state of coastal and shelf seas and their ecosystems are characterised by rapid temporal changes at spatial resolutions of the order of 100 m. River run-off, nutrient loads and contaminants have major influences on the system.

Knowledge of the changes in mass occurring in the Earth's interior, together with the mass exchanges between the cryosphere, atmosphere and the ocean, is required to properly quantify their relative contributions to sea-level change.

Ocean/sea-ice/atmosphere interactions taking place at high latitudes regulate the Earth's albedo, heat, momentum and gas exchange, and buoyancy forcing, and significantly influence water-mass properties. This in turn has significant consequences for deep-water formation, thermohaline circulation, and CO_2 sequestration, and thus governs the ocean's influence on climate.

To assess the current state of the ocean, its most likely evolution on time scales from days to a decade, and possible scenarios within the next century, a new paradigm for global data (space and in-situ) and model synthesis is needed. Existing data archives need to be fully exploited, with ocean re-analysis just becoming routine, while coupled ocean - atmosphere model-data synthesis is just on the horizon. Routine assessments of the oceans' heat, salt and CO_2 content on a monthly basis are needed to manage the global carbon system. Those assessments would provide the starting point for predictive systems addressing the dynamic ocean and the coupled climate system, and their interactions with the marine ecosystem. A decade-long set of such global data will provide unprecedented means to understand the dynamic ocean on a global scale and its interaction with the carbon cycle and the marine ecosystem.


ATMOSPHERE
stratosphere
protective natural ozone layer
troposphere
anthropogenic emissions
greenhouse effect

4.2 Atmosphere

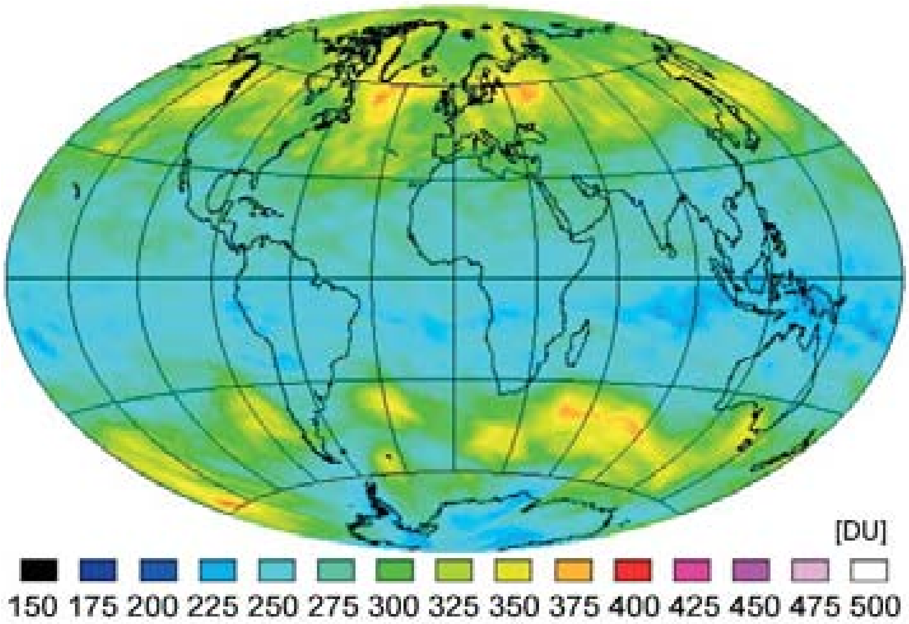
State of the art

In the last twenty years we have gone from having very few global observations from space to the extensive use of space observations to understand, model and forecast many aspects of the Earth System.

Substantial progress has been made in the area of Numerical Weather Prediction on short time scales (1-10 days), whereby the time span of useful forecasts has been extended from less than five days in the early 1980s to more than a week in recent years. This is particularly apparent in the last fifteen years, where the use of satellite data has implied a convergence of forecast quality between the Northern and Southern Hemispheres. Twenty years ago, the Northern Hemisphere forecasts were much better due to the availability of ground-based observations, which were very scarce in the Southern Hemisphere. Synoptic-time-scale (1-5 days) dynamical and physical processes in the mid-latitudes, driven by temperature, moisture and circulation patterns, are comparatively well-understood, and significant progress has been made in extracting the relevant information from satellite observations. In tropical regions, we still lack the appropriate satellite information (on winds) to achieve the same level of 1-5 day performance as obtained at mid-latitudes; the discrepancy arises because of a fundamental difference in the dynamical behaviour of the atmosphere in the tropics and at mid-latitudes. Despite these difficulties, operational coupled atmosphere–ocean forecast systems can exploit the memory of the tropical ocean to make useful seasonal forecasts of tropical events such as the El Niño - Southern Oscillation (ENSO) phenomenon.

There are still large uncertainties in climate predictions because of our lack of understanding of the coupling processes within the atmosphere, and the interactions between the different components of the Earth System. Clouds and their radiative feedbacks are a key issue in this context. In the IPCC Second Assessment report it is stated that: "The single largest uncertainty in determining the climate's sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation and their role in the hydrological cycle." This is further discussed in the IPCC Third Assessment Report, where it is concluded that increased availability of satellite measurements is needed to constrain the model-based estimates of climate sensitivity. Particularly in cloudy regions, such as the inter-tropical convergence zone, we need to improve the observational coverage of wind, temperature and humidity profiles. The global water cycle is also of central importance in this respect, due to its influence on the energy balance and its providing a link between atmosphere, ocean and land surfaces.

More recently, we have begun to get a global view and understanding of the global bio-geochemical cycles that are driving or mediating climate change. European scientists are building increasingly comprehensive Earth System modelling and assimilation capabilities, which will use satellite observations to deepen our scientific insight and extend our predictive capabilities. In preparing this 10-15 year forward look at the scientific challenges and requirements for observing programmes, full account is taken of the international consensus achieved in fora on scientific challenges such as IGOS-P, IGBP, WCRP, and GCOS.



Total-ozone forecast based on assimilated Envisat SCIAMACHY instrument observations.
Credit: KNMI/ESA

The continuous increase in greenhouse-gas concentrations is a matter of growing concern, as climate strongly depends on the distribution of greenhouse gases, but also aerosols. In turn, the distributions and concentrations of greenhouse gases are often strongly influenced by atmospheric chemistry, and chemical reactions are dependent on temperature and other climate parameters.

The ozone layer has undergone major changes in the last decades. Anthropogenic halogenated compounds are causing a thinning of the stratospheric ozone layer, and not only at polar latitudes. Over the last two decades, an average decrease of between 4% and 6% in total ozone has been found at mid-latitudes in the Northern and Southern Hemispheres, respectively. Ground-based observations have shown an increase in UV irradiance since the early 1980s of 6% to 14%, which are in agreement with estimates derived from satellite observations.

Recent satellite observations have demonstrated that air quality is a global problem. Consequently, there is a strong societal need for regular assessment and forecasting of air quality on kilometric to global scales. Air quality is mainly inversely proportional to the amounts of aerosols, nitrogen oxides, volatile organic compounds and ozone that are present. Aerosols also produce a direct radiative forcing of climate by virtue of their scattering and absorption of solar radiation, and an indirect forcing by changing the radiative properties of clouds. Quantitative understanding of the various sources of aerosols, their chemical composition as a function of size, and their sources and sinks is still poor. Nitrogen oxides are released into the troposphere by the combustion of fossil fuel, biomass burning and lightning. They are precursors, together with organic compounds, of ozone production in the troposphere. Accordingly, there is growing evidence for a continued increase in the ozone background concentration in the troposphere all over the World. The convective transport of pollutants from the surface into the free troposphere, where chemical lifetimes are often longer and the transport process much faster, make that issue a global one. In addition, ozone is also transported down from the stratosphere, but precise estimates are still lacking.

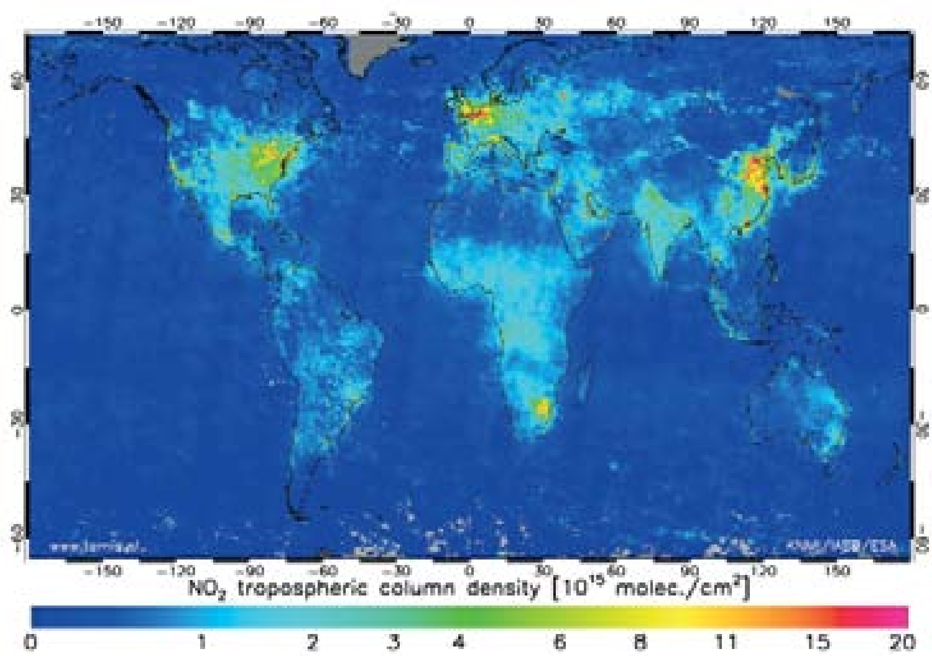
The Sun influences both interplanetary space and the Earth's atmospheric environment through its variable outputs of electromagnetic radiation and charged particles. The radiative properties of the Sun are the main component of the Earth's Radiation Budget (ERB), and its natural variability must be distinguished from the human-induced forcing effects. The charged particles are modulated by the Earth's magnetic field and have a direct as well as an indirect impact (through lightning) on the ionisation and electrical properties of the atmosphere. These properties are important for the dynamics of the upper atmosphere, the chemistry of active species, and electrically-mediated physical processes in clouds. Each of these processes may have a small effect individually, but they are poorly known. The response of atmospheric layers (troposphere-to-space) to varying forces at the boundaries – terrestrial surface and space – must be considered for robust predictions of climate trends and their dependence on human activity.

Challenges

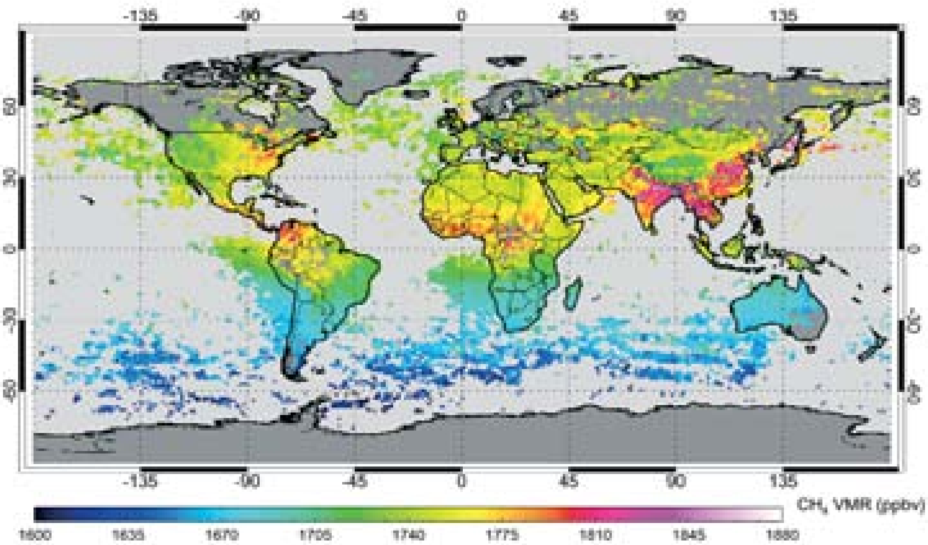
The main gap is currently the lack of a scientific basis for fully-coupled models which can describe the full complexity of the interactions of climate with clouds, chemistry, aerosols and dynamics, and the full complexity of the interactions of these processes with the ocean and land surfaces, including physical, chemical and biological elements of the interactions together with the essential data-assimilation capabilities based on the Earth System model. Such models must be able to treat statistically the impact of solid-Earth processes such as volcanism, while the data-assimilation system must be able to exploit the synergetic information on atmospheric, land and ocean processes contained in observations made primarily for, for example, gravimetric purposes.

A number of secondary gaps exist particularly in our ability to observe, understand and model processes at the interfaces of the domains into which the Earth System is normally partitioned. Important scientific questions are still open regarding the mechanisms and significance of the exchanges of trace constituents between the atmosphere and ocean (e.g. carbon dioxide, dimethyl sulphide…), and of water and other trace constituents between the atmosphere and land.

Human activity is, with high probability, the major source of changes in forcing mechanisms of the Earth's radiation budget and of the consequent climate changes over the past 50 years, but the amplitude of these forcings must be separated from the variability of natural forcing mechanisms due to the evolution of the planet and to the solar-terrestrial interaction. All of these forcings induce feedbacks due to dynamical, physical and chemical processes that drive changes in the Earth's radiation budget. The most important feedbacks involve winds, temperature, humidity and clouds as well as changes in the atmospheric composition. Understanding the role of feedbacks such as those from water vapour, aerosols and cirrus clouds, and reducing the uncertainties in our ability to describe these mechanisms, are prerequisites for



The mean tropospheric NO_2 content for 2003 as measured with Envisat's SCIAMACHY instrument. 'Hot spots' on this World map are the industrialised areas of Europe, China, the USA and South Africa. Many mega-cities elsewhere in the World can also be identified as localised spots with enhanced NO_2 concentrations.
Credit: KNMI/BIRA-IASB/ESA



Envisat SCIAMACHY instrument measurements of column-averaged methane volume mixing ratio (VMR), in parts per billion, averaged over the period August through November 2003 on a 1º x 1º horizontal grid. At least five (and up to 150) measurements are taken for each grid cell. Only a few observations are available over the ocean, since low ocean reflectivity substantially reduces the retrieval quality. Occasionally Sun glint or clouds at low altitudes do allow measurements over the ocean.
Credit: University of Heidelberg/ESA

the more reliable prediction of possible future climate scenarios. Adequate mitigation or adaptation strategies are needed to predict climate evolution on large scales and the coupling to smaller scales and to extreme events.

Air pollution has a major impact on human health, agricultural productivity and natural ecosystems. Air quality also plays an important role in climate-chemistry interactions. Air quality has several aspects: emissions, chemistry, sinks and transport. The sources and sinks of the species contributing to reduced air quality or its precursors, and their spatial and temporal variability, are poorly known. Moreover, the oxidising capacity of the troposphere is key in the transformation of species and in the cleaning of the atmosphere, but the stability of this aspect of tropospheric chemistry is uncertain. Furthermore, the long-range transport of pollutants makes air quality both a regional and a global problem. Quantification of this transport is very important, but observations are sparse. Another recent element in the air-quality and climate context is the influence of megacities. The consequences of the degradation of air quality on public health are quite dramatic. Moreover, decisions on the planning of cities and highways are strongly driven in several European countries by air quality and its expected development. Hence sustainability, management and mitigation of growing anthropogenic emissions is another important aspect of air quality.

Aerosols play a fundamental role in terms of both air quality and climate. Better knowledge about the formation and fate of aerosols is essential. In addition they strongly interact with clouds. Knowledge of the speciation of aerosols needs to be improved to quantify the radiative properties of the atmosphere. Knowledge of the vertical distributions of aerosols will improve due to satellite missions like Calipso, ADM-Aeolus and EarthCARE, but will still require further studies. The physical processes determining the life cycle of aerosols, e.g. vertical transport, and their complex interaction with clouds and tropospheric oxidants, need to be better quantified.

The composition and dynamics of the stratosphere are changing due to anthropogenic activities forcing climate change, but also due to emissions of chlorofluorocarbons. The latter emissions caused the ozone reduction in the last decades. The expected time scales for the ozone layer's recovery due to the reduction of emissions are now expected to get longer through the changing stratospheric concentrations of water vapour and carbon dioxide leading to lower temperatures. The Brewer-Dobson circulation determining the distribution of stratospheric ozone, but also the upward and downward transport from the troposphere to the stratosphere and vice versa, is an example of the intimate coupling between chemistry and dynamics. There are indications of changes in the Brewer-Dobson circulation, but further observations and modelling efforts are needed to understand their causes and consequences.

The Sun's impact on the stratosphere's composition and dynamics is known to be important, but recent satellite observations show a more complex behaviour of the stratosphere than was expected, and further observations are therefore needed.

The upper troposphere and lower stratosphere (UTLS) are strongly coupled both chemically and dynamically. Moreover, the changing composition of the UTLS has a strong impact on radiative forcing and therefore on climate change. Detailed observations of the composition in the UTLS are badly needed to better unravel the chemistry/climate interaction.

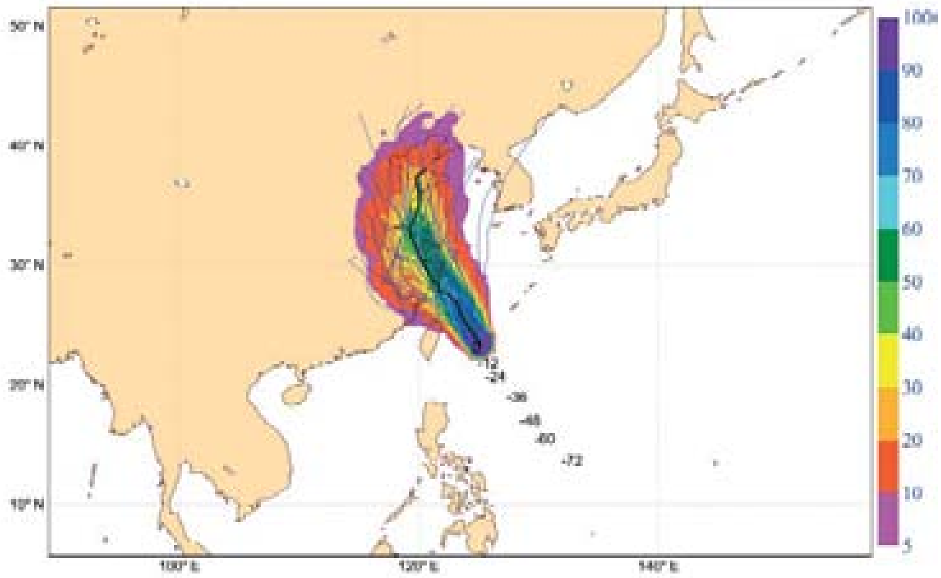
The UTLS exchange is partly determined by large spatial and temporal scale dynamical phenomena, but also smaller scales due to wave breaking, instabilities and deep convection. These different spatial and temporal scales call for demanding observational strategies using both ground-based and remote-sensing techniques.

Envisat's MERIS instrument acquired this image of Typhoon Matsa over the East China Sea on 4 August 2005 at a spatial resolution of 300 m.
Credit: ESA

Global climate change involves a change in the mean state of the atmosphere, as well as changes in the variability of circulation patterns and extreme weather events. The variability of large-scale circulation systems can have an impact on, for instance, crop growth and the spread of disease. Extreme weather events may pose serious threats to life and economic development in many different societies, as shown by the death and destruction caused by recent events such as the 1998 El Niño, the heat wave in 2003 and floods in 2004 in Europe, and the inundation of New Orleans in 2005 following Hurricane Katrina. These changes involve complex and inadequately understood processes within the atmosphere, including interactions of dynamical, wind and pressure fields with radiation, clouds, convection, turbulence in the planetary boundary layer, and also interactions with chemical processes. In addition, these events involve complex dynamical, physical and chemical interactions with the upper ocean, and with land, including hydrology and the biosphere in the ocean and on land.

Understanding all of these interacting processes is a central challenge to the science of climate and weather. Only through active interdisciplinary research on Earth System models, and more refined observation of the Earth System from space, will the vital advances in the scientific understanding of the coupled processes be achieved. Such advances will lead directly to better predictions and thus to better management of society's response to these threats across a range of lead times from days and weeks to seasons and years.

Since continued long-term changes in atmospheric composition may exacerbate the frequency and intensity of extreme climate and weather events, as well as modify the agricultural and health conditions, there is an urgent need for further improvements in our scientific understanding for the planning of the adaptation/mitigation measures needed to achieve sustainable development.



Strike probability map for Typhoon Matsa, starting from the ECMWF analysis of 4 August 2005 00UTC. The ECMWF operates a so-called ‘Ensemble Plotting System’ (EPS) in which, in addition to the operational high-resolution forecast (OPER), other alternative forecasts are made at a lower resolution.

Credit: ECMWF

Given the current mission planning in Europe and elsewhere with, for example, MetOp, NPOESS, ADM-Aeolus, EarthCARE and GPM, the priorities for new Earth Explorer missions in the atmospheric domain are twofold. One priority is to address the issue of the sensitivity of climate and atmospheric circulation to changes in cloud radiative and precipitation properties resulting from changes in atmospheric composition, such as greenhouse gases, aerosols and reactive gases. Of equal priority is the need for detailed space observations of the processes governing: (i) changes in air quality and atmospheric composition in the lower troposphere and (ii) changes in atmospheric composition in the upper troposphere and lower stratosphere.

Observations

Ground-based networks provide the current global observations for surface values, and vertical profiles of temperature, wind, water-vapour content, clouds and atmospheric composition. In addition, observations of total columns and profiles of trace constituents are provided. However, many gaps exist in ground-based network coverage, in measurement methodology and

The Challenges of the Atmosphere

Challenge 1: Understand and quantify the natural variability and the human-induced changes in the Earth’s climate system.

Challenge 2: Understand, model and forecast atmospheric composition and air quality on adequate temporal and spatial scales, using ground-based and satellite data.

Challenge 3: Better quantification of the physical processes determining the life cycle of aerosols and their interaction with clouds.

Challenge 4: Observe, monitor and understand the chemistry-dynamics coupling of the stratospheric and upper tropospheric circulations, and the apparent changes in these circulations.

Challenge 5: Contribute to sustainable development through interdisciplinary research on climate circulation patterns and extreme events.

data archiving. There is a need for continuing global observations from satellites and from the ground to improve our understanding of atmospheric dynamics, thermodynamics and composition.

EarthCARE, Cloudsat and Calipso will allow major progress in the understanding of aerosols and cloud processes. ADM-Aeolus, by measuring wind profiles, will play a major role in proving the concept of space Doppler wind lidar and preparing for future operational missions. IASI and GOME on MetOp will provide some information on atmospheric composition and the ozone layer.

Firstly, three-dimensional space observations are available for atmospheric chemistry from Envisat and EOS-Aura, but more detailed observations on dynamics, thermodynamics and chemical composition are needed, including more advanced measurements with better capabilities including better spatial and temporal resolution. In addition, sustained observations of wind and the Earth's radiation budget (ERB), and a better characterisation of cirrus clouds and precipitation, in particular solid precipitation, are needed.

The radiative energy balance of the Earth is a fundamental driving process of the climate system. Observing the magnitude and variability in time and space of the ERB provides an extremely powerful constraint on climate models. Measurements are available now from US polar-orbiting instruments such as the CERES on the Aura and Aqua satellites, and from the Meteosat Second Generation satellite series via the GERB experiment, although there are no plans for the long-term observations that are vital for climate-change studies.

In this field, the major missing observation is that of spectrally resolved measurements at moderate resolution of both long-wave and short-wave fluxes. Such measurements would allow us to delve into the individual processes responsible for changes in the ERB.

System approach

To unravel the full complexity of the coupled Earth System, improved observations, models and data assimilation are essential. There is a need for an end-to-end system approach comprising observations, retrieval algorithms, validation, scientific data analysis, archives, models, assimilation systems, and science and service delivery.

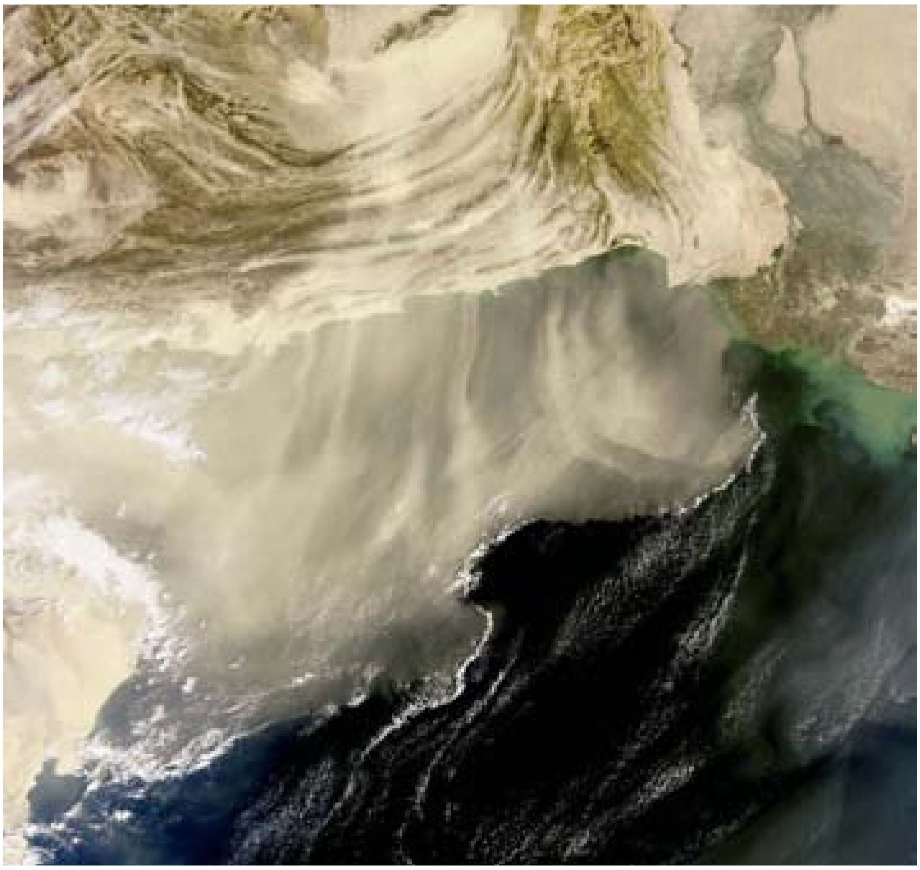
Ground-based observations are absolutely necessary on a long-term basis as a central pillar of the observation portfolio. They also provide essential validation of space observations.

A comprehensive European Earth System data-assimilation capability is needed as part of the end-to-end system for science delivery and for the transition to operations.

Re-analyses of archived time-series of previous data with the latest scientific developments will be required and will need sustained work on algorithms for observation processing.

The observation strategy must be based on the integrated strategic approach defined by the IGOS and, in particular, IGACO for atmospheric composition.

Many opportunities exist for synergies between disciplines in science and in observational techniques. The Earth System also comprises biological, physical and chemical exchanges between oceans, continents and the atmosphere. The main components of the Earth System interacting with the atmosphere are the land surfaces and the oceans. The atmosphere is exchanging momentum, heat, water, carbon and all trace gases and aerosols with ocean and land surfaces. Sea-surface temperature, soil moisture, surface albedo and the composition of the atmosphere influence the atmospheric circulation. Therefore, space observations of these quantities are important to understand and forecast the motion and the composition of the atmosphere (chemical weather forecast). The atmosphere, in turn, drives the ocean currents and the ocean waves, and space observations of these quantities are used as an indirect assessment of the quality of these forecasts.



This MERIS instrument image of 13 December 2003 is dominated by a dust and sand storm covering the Gulf of Oman. The scene includes a large part of Baluchistan, a mountainous region with some deserts and barren plains, and parts of southwestern Pakistan and southeastern Iran (top right & top centre). It shows the interaction of dust particles (aerosols) of a continental air-mass interacting with a humid marine boundary layer (Somali jet), leading to cloud development at the edge of the outbreak.
Credit: ESA


CRYOSPHERE

4.3 Cryosphere

The term ‘cryosphere’ collectively describes all forms of frozen water on and near the Earth’s surface, namely sea ice, ice sheets, glaciers, snow cover, solid precipitation, river and lake ice, permafrost and seasonally frozen ground.

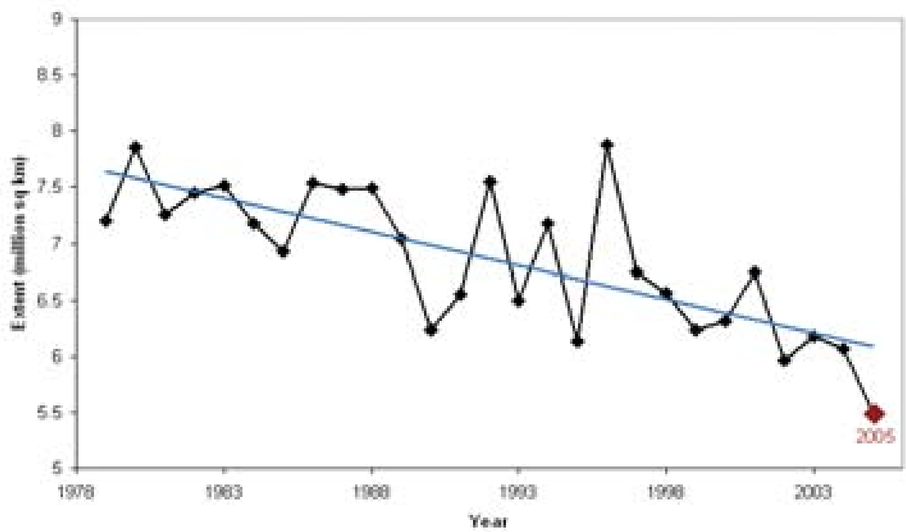
State of the art

During the course of the twentieth century, it became clear that the cryosphere was more than just an inhospitable environment, remote both geographically and in terms of relevance to the majority of the Earth’s population. Climate-model simulations now suggest that northern high-latitude regions will reveal a dramatic effect of global warming to the extent that a number of models predict a sea-ice-free Arctic Ocean during the summer, from about 2060 onwards. Moreover, associated changes in the masses of the large ice sheets and glaciers are expected to have an impact on the thermohaline circulation of the oceans, as well as the eustatic component of sea-level rise. Meanwhile, associated changes in the high-latitude distribution of permafrost and seasonal snow cover will have complex impacts on the hydrological cycle, the release of trace gases and high-latitude ecosystems. The picture today is one in which the cryosphere reacts sensitively to climate change, but more importantly provides yet-to-be-defined feedback to the rest of the planet through a number of complex and intertwined processes involving the land, ocean and atmosphere environments.

The conventional means of measuring sea-ice thickness is with an auger, in this case off the coast of Alert, Canada, during preparations for the validation of CryoSat altimeter-derived sea-ice thickness measurements.

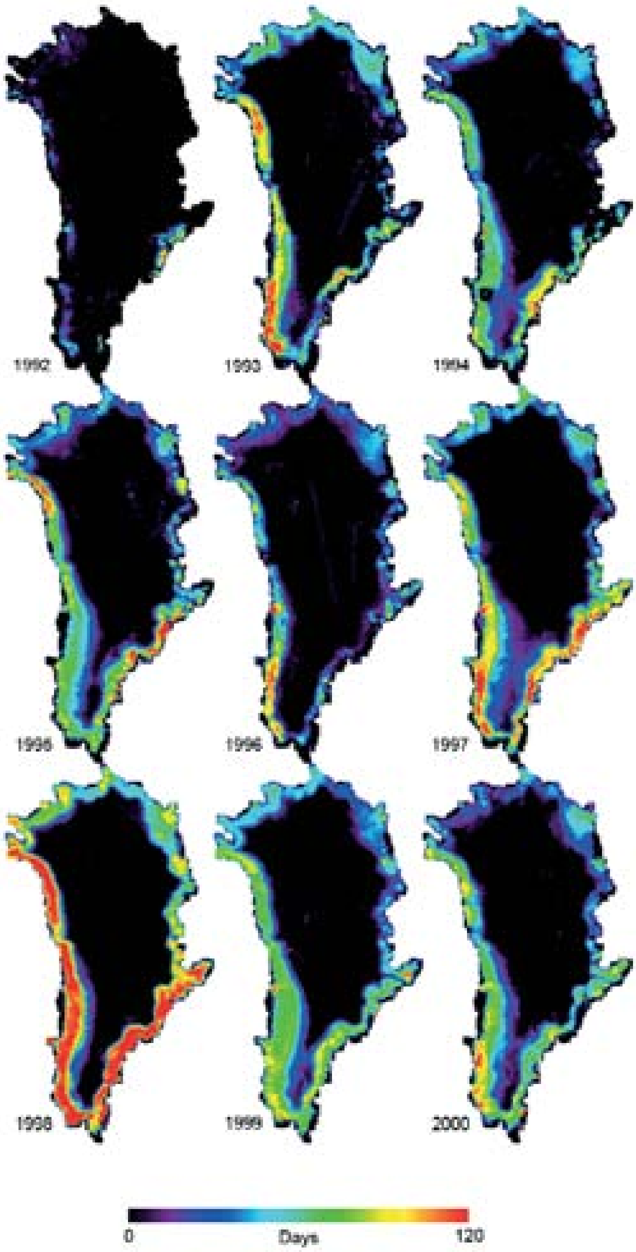
Credit: R. Forsberg, Danish Space Research Institute

It is difficult to overestimate the role that satellite observations have played in helping us to reach our current level of understanding of the cryosphere, beginning with the advent of routine, all-weather, day-and-night, satellite-borne passive-microwave observations in the 1970s. Twenty-five years of consistent long-term observations by a series of satellite microwave radiometers have revealed a dramatic decline in Northern Hemisphere sea-ice concentration and extent, at a rate of about 3% per decade. Meanwhile, though some of the most dramatic warming has occurred in the vicinity of the Antarctic peninsula, no conclusive trend is evident in the cover of Southern Ocean sea ice. More recently, scatterometers have augmented the passive-microwave record and both, along with buoys, have been used to monitor ice drift, to the point where this is now almost routine and beginning to be assimilated into models. This is an initial step in defining the specific role of sea-ice dynamics in the climate system, but sea-ice rheology and mass variability and redistribution are still poorly understood.



Decline in Arctic sea-ice extent in the month of September from 1979 to 2005, amounting to more than 8% per decade. ‘Ice extent’ is defined as an ice concentration of 15% or greater.

Credit: National Snow and Ice Data Center

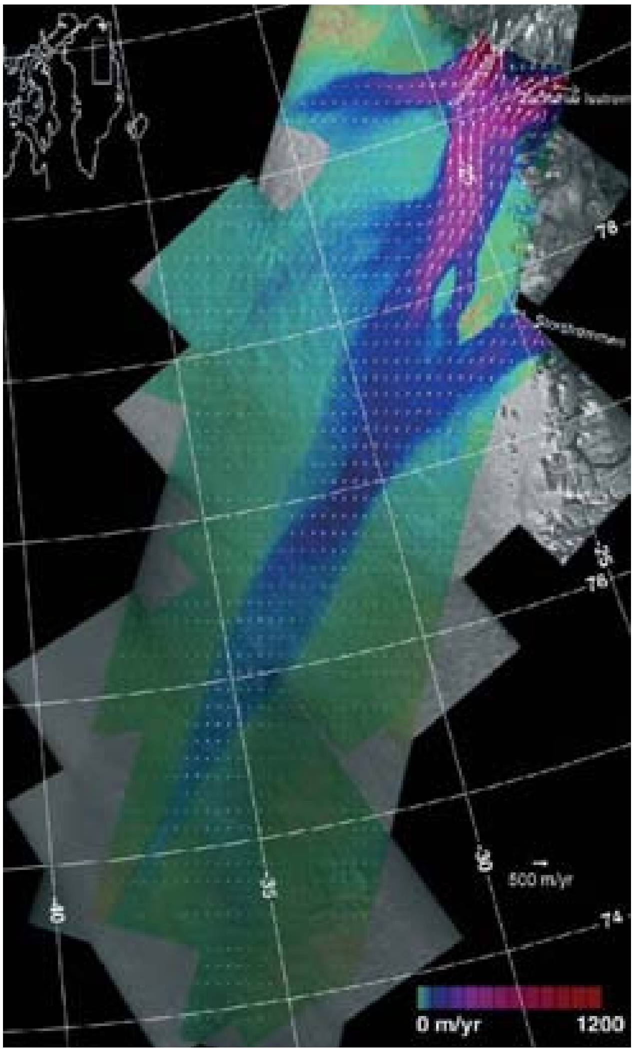


Greenland ice-sheet surface melt duration, estimated using ERS Scatterometer image data.

Credit: I. Ashcraft, Brigham Young University

For the ice sheets and glaciers, key sensors have been synthetic-aperture radar and satellite altimetry, with a major contribution from the 14-year record provided by ERS-1, ERS-2 and Envisat. SAR has been used to map the ice sheets with unprecedented detail and interferometric-SAR (InSAR) applications, in particular during the ERS-1/-2 Tandem operations, have demonstrated the impact of streaming ice flow for the regional ice-sheet mass balance, together with the critical importance of the rate of ice-stream flow and ice-shelf decay to the overall stability of the large ice sheets. Altimeter time-series have, in conjunction with SAR observations, characterised seasonal to inter-annual changes in ice-sheet elevation and topography over moderately sloping regions from basin to continental scale. These data indicate that, although the central parts of the large ice sheets appear stable and in balance, dramatic changes are taking place around their more dynamic margins, in particular around the West Antarctic ice sheet and around Greenland. Inland migration of grounding lines in areas of streaming ice flow, and the dramatic disintegration of ice shelves such as the Larsen in Antarctica, indicate that the ice-sheet and ice-shelf dynamics may be considerably more sensitive to short-term climate fluctuations than formerly believed. The combination of SAR and satellite altimetry is helping to constrain the uncertainty in the contemporary mass balance of the ice sheets, although not yet to the level required to be confident about their overall stability. Additional information, such as ice thickness, is needed to advance the knowledge of ice-flow dynamics. Satellites observe the rapid decrease in glacier area worldwide, but better data on mass-balance and volume changes are needed to fully understand the climate response and their impact on hydrology and water resources.

The long-term passive-microwave records, and the more recent scatterometer and SAR data, indicate that snow seasonally covers up to 30% of the land surface. Snow-cover changes therefore exert a large influence on both the radiation and freshwater balances. As global warming proceeds, it is predicted that regions currently receiving snowfall will increasingly receive precipitation in the form of rain, and for every 1°C increase in temperature the snowline will rise by about 150 metres. Climate models indicate that temperate Alpine regions are likely to experience milder winters with more precipitation, but drier summers in the future. Such conditions are not conducive to a seasonal snow cover on the mountains since, in most temperate mountain regions, the snow temperature is close to the melting point and therefore very sensitive to changes in temperature. High-resolution sensors, notably SAR, play a role in assessing glacier mass balance and snow cover. There has been some success in the integration of basin-scale hydrological



The Northeast Greenland Ice Stream, first discovered in an ERS-1 Synthetic Aperture Radar (SAR) image mosaic. Ice-flow speed is indicated by the colour scale, while velocity vectors appear as white arrows.

Credit: I. Joughin/JPL, APL, Univ. of Washington.
ERS images copyright ESA, 1992-1996

Sea-ice drift in the Weddell Sea, Antarctica, derived using 1 km-resolution Envisat ASAR Global Mode data acquired over six days in 2004. Arrows indicate 3-day drift over the intervals 30 September – 3 October (Blue); 1-4 October (Red); and 2-5 October (Green).

Credit: L. Pedersen, ESA PolarView Study Consortium

models with observations taken in part from these sensors, although poor knowledge of the snow mass hampers further progress.

Perennially frozen ground (i.e. permafrost) is estimated to underlie 24% of the exposed Northern Hemisphere land area. Permafrost has an important regulative function on water and energy fluxes, and on the exchange of carbon and trace gases between the land and the atmosphere. Fluxes of trace gases from northern ecosystems represent a highly uncertain contributor to future global change, and in-situ observations suggest that global warming will strongly modify these fluxes. The wet lowlands of the Arctic permafrost landscapes, for example, are important natural sources of the greenhouse-gas methane. Recent satellite observations have detected accelerated melting of Siberian bogs, which may unleash large amounts of methane, thereby amplifying global warming. Continuous observations of permafrost extent and characteristics are needed to assess the role of the permafrost regions in global and and regional energy, water and carbon cycles. Scatterometers and SAR have been used to observe morphological and hydrological characteristics of permafrost areas, but more systematic observations at high spatial resolution are needed.

Challenges

Our overriding objective is to quantify the impacts of climatic variability and change on the cryosphere, and to assess the consequences of these changes for the climate system and the living environment as a whole. Although satellite observations have revealed significant changes taking place to the cryosphere, the attribution of these changes to either anthropogenic or natural causes remains unclear. Key measurements are not yet available, which limits our ability to characterise the overall behaviour of major elements of the cryosphere and to assess the nature of cryosphere interaction with the oceans, atmosphere and terrestrial systems.

The major challenges are:

- We need to quantify the mass and freshwater balance and distribution of sea ice, and current and possible future feedbacks to the ocean and atmosphere. Our ability to achieve this is limited in particular by poor knowledge of sea-ice thickness distribution, but also by other uncertainties including ice rheology, perennial ice distribution, snow cover and albedo.
- We need to calculate the mass balance of ice sheets, ice caps and glaciers, to assess their contribution to eustatic sea level, and to evaluate their sensitivity to forcing. We have limited knowledge of boundary conditions, including basal topography and snow accumulation rates, and we have carried out insufficient baseline and repeat surveying of a range of conditions around the dynamically important ice-sheet margins and across the many smaller ice caps and glaciers. As a result, we are not yet well-placed to assess the current and potential cryospheric impact on sea level and the water cycle. Furthermore, we have a need to quantify the contribution of floating ice shelves and icebergs to the global freshwater balance and the implications for water-mass properties and ocean circulation.
- It is important that we compile a quantitative assessment of changes in snow water equivalent and solid precipitation and understand their impacts on the global hydrological cycle and regional water resources. These changes also need to be linked to atmospheric processes in order to understand the broader climatic picture.
- The current and potential impact of the cryosphere on energy, moisture and trace-gas fluxes between the land, atmosphere and ocean needs to be evaluated. Frozen ground and permafrost act to constrain physical and bio-geochemical processes and remain largely untreated in present-day climate models. As a result, fluxes of trace gases from northern ecosystems, along with hydrological and energy flux changes, represent highly uncertain components of future global change.

The Challenges of the Cryosphere

Challenge 1: Quantify the distribution of sea-ice mass and freshwater equivalent, assess the sensitivity of sea ice to climate change, and understand thermodynamic and dynamic feedbacks to the ocean and atmosphere.

Challenge 2: Quantify the mass balance of grounded ice sheets, ice caps and glaciers, partition their relative contributions to global eustatic sea-level change, and understand their future sensitivity to climate change through dynamic processes.

Challenge 3: Understand the role of snow and glaciers in influencing the global water cycle and regional water resources, identify links to the atmosphere, and assess likely future trends.

Challenge 4: Quantify the influence of ice shelves, high-latitude river run-off and land ice melt on global thermohaline circulation, and understand the sensitivity of each of these fresh-water sources to future climate change.

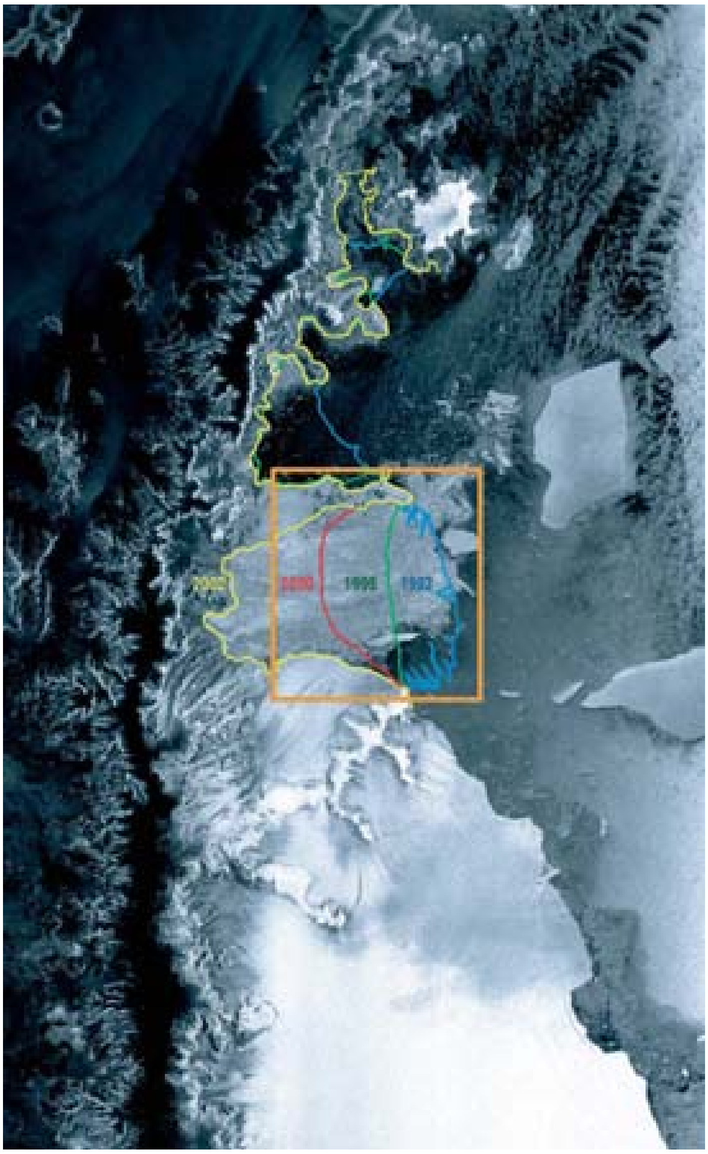
Challenge 5: Quantify current changes taking place in permafrost and frozen-ground regimes, understand their feedback to other components of the climate system, and evaluate their sensitivity to future climate forcing.

If these challenges are met, then we have the prospect of significantly improving the parameterisation of cryospheric processes in coupled ice–ocean–atmosphere models and thus predicting the role of the cryosphere in climate change, as well as its impact on regional water resources, the biosphere and natural hazards. Efficient progress in meeting these challenges demands the parallel development of improved spatially-distributed models and data-assimilation tools for the effective combination of in-situ and satellite observations in these models. Data assimilation will also benefit from retroactive modelling of historical ice conditions, which in turn will significantly improve the initial conditions used to spin-up climate models.

Observations

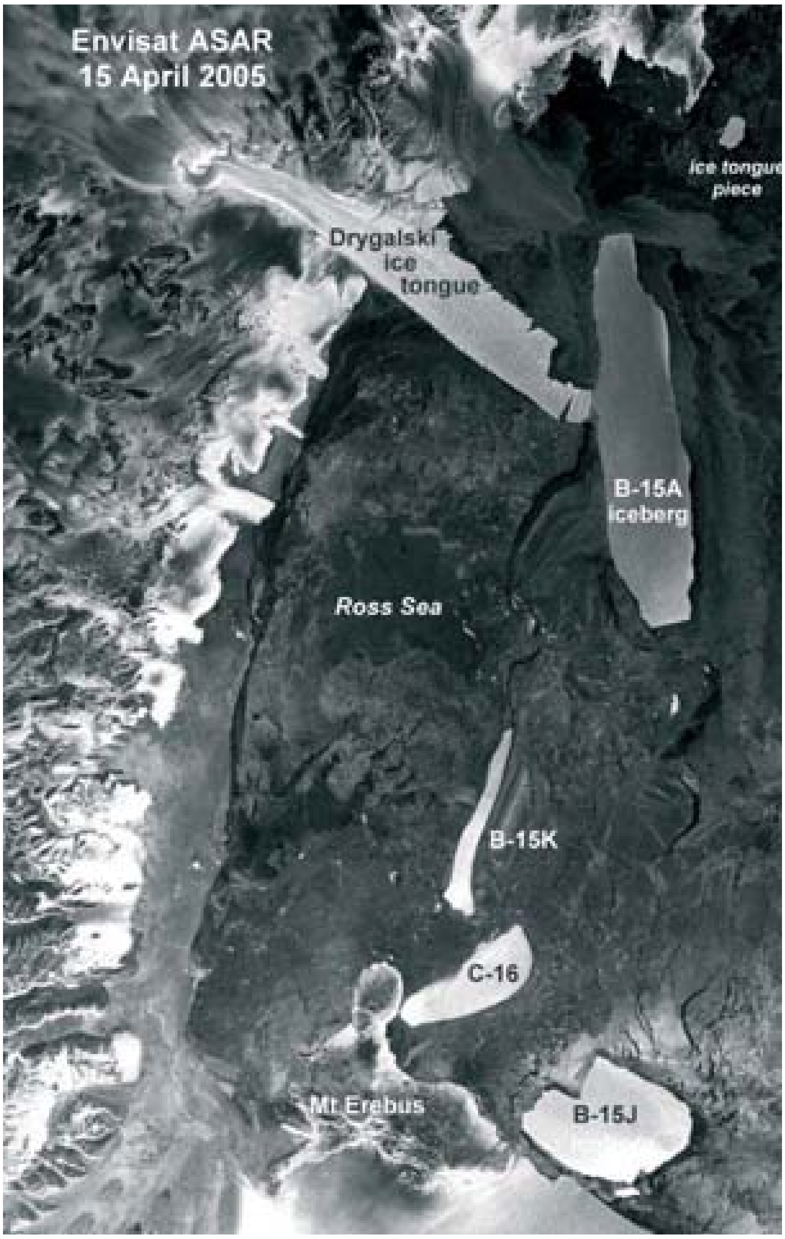
Continuous, uniform, long-term monitoring observations are the key to assessing the response of the global cryosphere to climatic variations. Due to large year-to-year variations in the amplitude of seasonal signals, the duration of monitoring records has a critical impact on the certainty with which trends can be assessed. Meanwhile, high temporal and spatial resolution observations are needed to characterise rapid variations in snow and ice in response to the processes that modulate fluxes of momentum, heat, freshwater and gases at the surface.

To address these observational requirements effectively, a combination of routine, broad-swath,



Envisat ASAR image of the18 March 2002 collapse of the Larsen Ice Shelf together with earlier positions of the shelf ice margin.

Credit: H. Rott, Univ. of Innsbruck & ESA



Envisat ASAR image of the Scott Coast, Antarctica, showing the collision of the B15A iceberg with the Drygalski ice tongue in April 2005.
Credit: ESA

low-resolution, global-monitoring instruments (microwave and optical) and specialised, high-resolution, narrow-swath data are required. New findings from current and forthcoming satellite observations, combined with more routine observations from present and future SAR, scatterometer and passive-microwave missions, will advance our ability to sustain the optimum satellite observing system for the cryosphere.

For ice sheets, we need to collect observations over a sufficiently long period of time to enable mass balance to be calculated within acceptable error bars. This translates into observations of surface elevation, velocities, surface accumulation and ablation. Combinations of laser and SAR interferometric radar altimetry are needed to map the topographic variations in the coastal areas of the large ice sheets, as well as in small ice caps and glaciers. These methods must be complemented by spatially-contiguous InSAR observations. Such repeat-pass InSAR measurements must be optimised to mitigate the short de-correlation time scale and the geometric limitations imposed by steep topography or mountainous areas. Together, these two techniques can provide mass-balance information in the most dynamically sensitive regions of the ice sheets.

To complement improved knowledge of contemporary changes taking place at the surface of the ice sheets, information on internal and basal conditions is required. Together, parameters comprising ice thickness, basal topography and bottom conditions set critical boundary conditions that regulate ice flow velocity and its variability in time and space. Presently, these parameters are unknown over large parts of the Greenland and Antarctic ice sheets. Low-frequency (P-band) sounding radar offers the potential for ice-thickness determination in cold ice, and mapping of echoes from internal layering and the flow-induced ice fabric variations. Such data would provide insight into factors controlling the present-day interior dynamics of the ice sheets as well as the context of their flow history for millennial time-scale, ice-sheet change reconstructions.

Regarding global snow cover, high-frequency active microwave and optical techniques are required to resolve inter-annual fluctuations and to provide effective monitoring of essential snow conditions such as depth, water equivalent and albedo. To complete the mass-balance equation, information on snow accumulation rate on the ice sheets is also required. Such a snow-accumulation and snow-characteristics capability should, in principle, be used to address snow cover on ice-sheet, glacier, sea-ice and land surfaces.

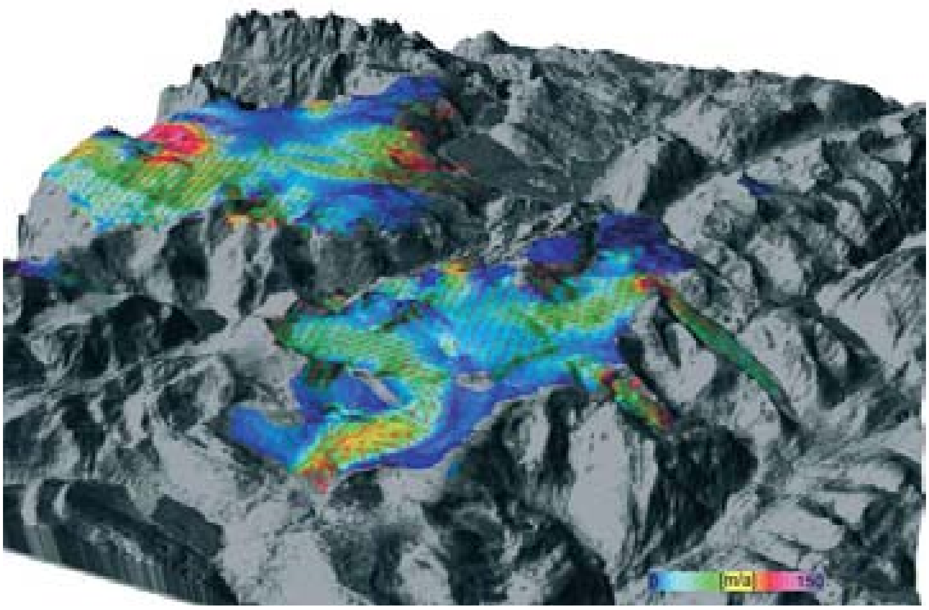
A major shortcoming in polar research is the lack of reliable information on the large-scale distribution of sea-ice thickness and snow depth on sea ice. New techniques applying delay-Doppler radar and laser altimeters are planned to resolve the ice-thickness challenge. However, the lack of useful snow-cover statistics limits retrievals of sea-ice thickness from altimetry-based methods. Whilst collocated measurements from laser and radar altimeters may provide some indication of the impact of regional seasonal and inter-annual variability in ice thickness and snow depth, uncertainties resulting from conversion from sea-ice surface elevation to thickness clearly warrant development of a direct snow-depth measurement technique.

Spatially detailed, repeat observations of snow cover, permafrost extent and properties, surface water and wetlands in high-latitude areas are needed to better understand and assess the response and feedbacks of permafrost regions to changes in the climate system. New satellite-observation techniques are required to determine the seasonal and long-term changes in permafrost extent, and to study the associated climate effects on water, energy and trace-gas fluxes.

Finally, as well as developing sensors that are able to directly measure these parameters, new techniques to extract information from existing satellite sensors should continue to be assessed. Existing L-band GNSS signals-of-opportunity and complementary L-band radiometry, for example, can be explored for the measurement of cryospheric parameters such as ice-sheet thermometry, and the distribution of leads in the sea-ice pack.

System approach

The dynamic nature of the cryosphere and its complex physical, chemical and biological interactions with other components of the Earth System, help to drive climate variability and make it imperative to adopt a system-wide perspective on climate. An improved understanding of the links between the physical environment and bio-geochemical processes can only be gained via



Topography and flow of ice in the Norwegian Svartisen complex of mountain glaciers, derived from Interferometric SAR measurements. Colours indicate variations in the ice flow (in metres per year), with arrows indicating the direction of flow.
Credit: T. Nagler, ENVEO & ESA

interdisciplinary studies that include snow and ice geophysics in combination with atmospheric, oceanic and biological sciences.

For ice-sheet mass balance and dynamics, there is a need to integrate cryospheric observations with those of gravity, to distinguish the effects of cryospheric processes from processes such as post-glacial rebound, a reflection of the very challenging precision required. There is also a need for detailed characterisation of the spatial distribution of snow accumulation, surface velocity and ablation with internal and basal properties of the ice sheets, which will require combining data from different satellite missions and sensors. It is also important to link these to in-situ observations and to ice-sheet models, both of which provide the temporal context and allow process diagnosis.

Sea-ice mass and freshwater balance and processes require integration with observations of ocean salinity, solid precipitation and snow-cover missions. In-situ observations of river run-off and subsurface ocean properties are also critical for completing the list of required observables. Coupled ice–ocean models are then needed to draw together the various elements with atmospheric forcing scenarios.

Studies of glacier mass balance and links to the water cycle and regional water resources need to be carried out within the context of hydrological models, and need to be augmented by data from in-situ gauges, soil moisture and snow-cover missions. Water resources supplied by glacier and snow melt are declining in many regions, and improved knowledge of the relevant processes will help to better adjust to the changing conditions. Such an integrated approach can also help in improving protection from natural hazards caused by snow-melt floods, glacier-water outbreaks, and avalanches.

The interdisciplinary and system-level approach to the cryosphere-specific scientific challenges will be increasingly driven by the modelling community. For instance, exchanges of freshwater between elements of the cryosphere and the oceans and atmosphere have a significant impact in terms of generating seasonal and longer-term mass and gravity anomalies. A comprehensive assessment of the integrated effects of the large-scale redistribution of mass and its impact on isostatic adjustment, and the Earth's rotation, require a synthesis of the solid-Earth and ocean–atmosphere–ice coupled modelling approaches.

A broad interdisciplinary approach is also needed in the context of coordinated satellite Earth observations from different sensors and platforms, and even different space agencies. For the oceans, there is a need to more effectively link cryospheric missions with those that address parameters such as ocean salinity. For the atmosphere, there is a pressing need to link tropospheric sounding observations and those that supply near-surface energy-balance measurements (e.g. surface turbulent fluxes) to cryospheric missions. In many cases, in-situ observations are a necessary element of the mix of observations required to derive robust results.

Permafrost and frozen-ground environments are extremely complex and can only be approached by integration with a broad range of tools and data sources. The permafrost challenge in particular requires rather sophisticated remote sensing of soil properties, vegetation, snow pack, trace gases and hydrological and climate parameters. A comprehensive, integrated view of the atmospheric, biospheric and cryosphere processes will be required to improve climate-model parameterisations of these complex feedbacks.

Such fundamental gaps in our knowledge of feedback processes in the cryosphere call for a truly interdisciplinary approach.

Impact of climate-related permafrost degradation on a building in Yukon, Alaska.
Photo: K. Maharaj, inHerEye Photography


BIOSPHERE

4.4 Land Surface

State of the art

The land surface is affected by a myriad of bio-geochemical and bio-geophysical processes, and is coupled to climate through a wide range of driving and feedback mechanisms. However, we are now in an era where accelerating anthropogenic interference dominates large parts of the land surface, with significant effects for the whole Earth System. The growing human population and improved standards of living are placing ever-increasing demands and stresses on ecosystem services provided by the land. We are increasingly aware that there are limits to what the system can bear, and that sustainable management of land ecosystems is of crucial importance.

Over the last few decades, significant advances have been made in quantitatively describing the bio-geophysical and bio-geochemical processes influencing the land surface. There is an increased awareness of the accelerating changes in the structure of the land surface and of the importance of spatial heterogeneity and fragmentation of the landscape. Also, modelling of the land-surface interactions with other components of the Earth System has significantly advanced.

In parallel with the improved understanding of land-surface processes, there have been major improvements in airborne and space-borne observations of the chemical composition of the biotic and abiotic environment, surface energy balance, surface hydrology, vegetation transpiration and structure. However, there are still major gaps in global and regional monitoring systems that prevent the derivation of well-documented time-series for many ecosystem variables. These gaps pose significant barriers in assessing status and trends in ecosystem services. Moreover, in some countries long-term in-situ monitoring systems are declining.

For regions with longer term in-situ observations and derived time series of ecosystem variables, these series often offset each other in terms of duration, and trends of opposite sign are observed. Also accurate measurements of land-cover change are only available on a case-study basis.

Challenges

Many land-surface features and processes of global significance occur at the local scale and must be extrapolated to regional and global scales taking into account their spatial variations. The processes that link biospheric phenomena, surface/atmosphere interactions and ecosystem processes are not yet adequately parameterised on all the relevant scales. Of particular concern are the current rather crude parameterisations of the main land-surface processes in Earth System models, which constitute one of the major limitations for climate projections. The current inability to understand and predict the impacts of a growing population and increased utilisation of natural resources is also a major challenge.

The challenges mentioned above are linked to the following issues:

- **The water cycle** determines the availability, quality and distribution of water for biological processes on the land. It plays a major part in transporting energy, minerals and nutrients. In addition, the availability of water is becoming a key factor affecting the global distribution of the human population.

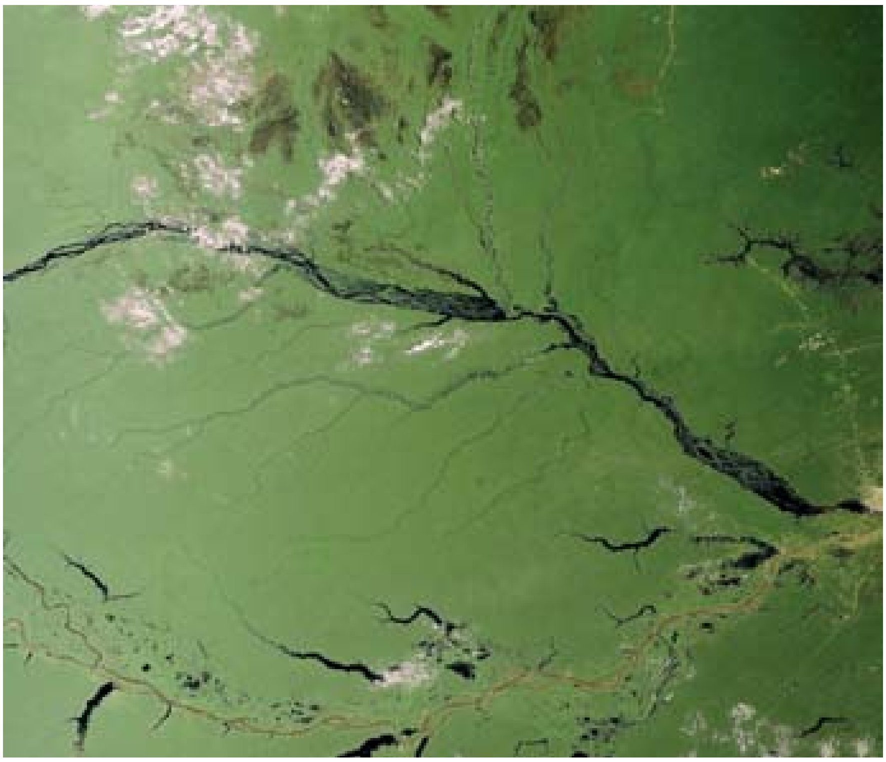
- **The carbon cycle and carbon sequestration:** Vegetation is the key component of the terrestrial biosphere in terms of biomass production, and its role in biochemical cycles and surface/atmosphere interactions. Improved understanding of the functioning of biomas and different vegetation types would allow better estimation of the stocks, fluxes and processes of the terrestrial carbon exchange.

- **The structure and dynamics of terrestrial ecosystems** are determined by many drivers such as climate, uplift, deformation and breakdown of bedrock, erosion, transport and deposition of sediment, life and particularly human action.

- **Biological diversity** is a key to the resilience of the biological system on the land surface. It interacts with relevant ecosystem characteristics such as structure, nutrient cycling, productivity and vulnerability.

- **Land-use and land-cover change** determine to a large extent the energy and matter fluxes across the land surface. Human activity has changed land cover significantly in order to supply resources for society. In particular, urban development and the construction of anthropogenic infrastructure have significantly altered terrestrial ecosystems.

- **Dynamics of human population:** population growth and increasing wealth consume more natural resources and put growing pressure on nearly all terrestrial ecosystems.



Envisat MERIS image of a large part of the Amazon Basin in Brazil. The area is a low-lying valley almost entirely covered by tropical rainforest. A peculiarity of the Amazon River is the paucity of settlements along the river's banks, in contrast to the usual large ports, transport hubs and industrialised cities along most important waterways. Manaus, one of only three sizable cities on the banks of the Amazon, is to the right of the image, just north of the confluence.
Credit: ESA

The Challenges of the Land Surface

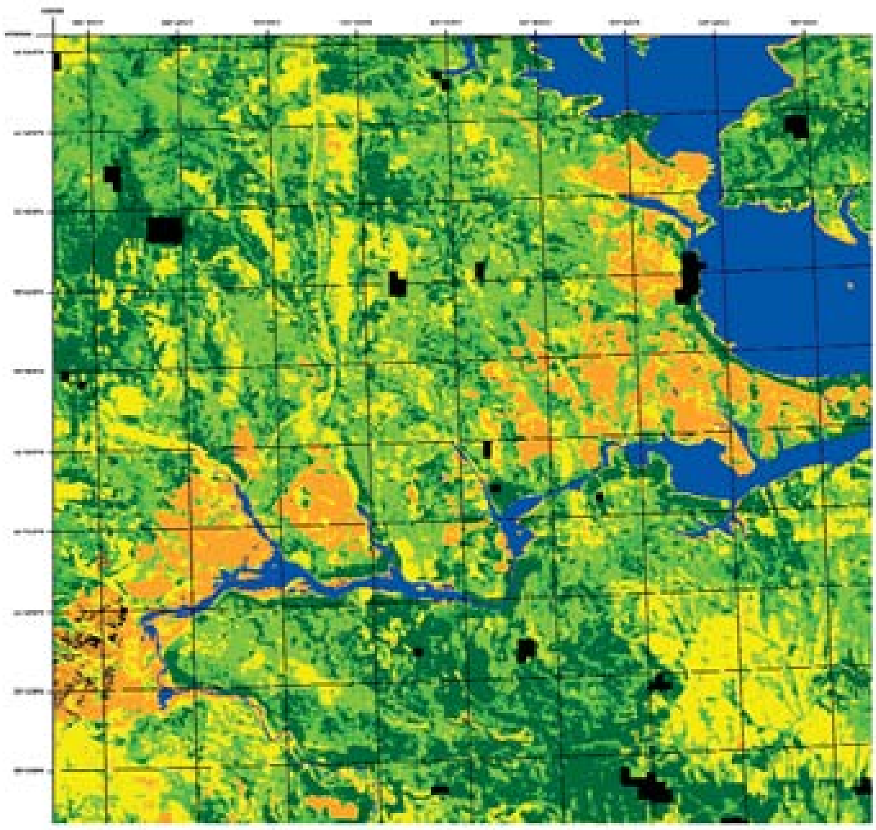
Challenge 1: Understand the role of terrestrial ecosystems and their interaction with other components of the Earth System for the exchange of water, carbon and energy, including the quantification of the ecological, atmospheric, chemical and anthropogenic processes that control these biochemical fluxes.

Challenge 2: Understand the interactions between biological diversity, climate variability and key ecosystem characteristics and processes, such as productivity, structure, nutrient cycling, water redistribution and vulnerability.

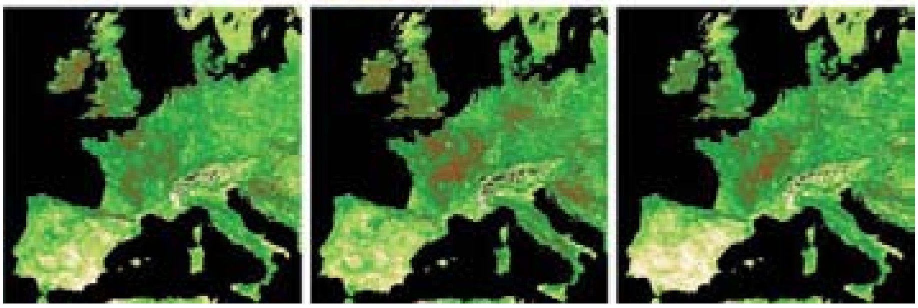
Challenge 3: Understand the pressure caused by anthropogenic dynamics on land surfaces (use of natural resources, and land-use and land-cover change) and their impact on the functioning of terrestrial ecosystems.

Challenge 4: Understand the effect of land-surface status on the terrestrial carbon cycle and its dynamics by quantifying their control and feedback mechanisms for determining future trends.

The use of Earth observation from space for an improved understanding of land-surface processes has to enhance the predictive capabilities of available numerical models. A major limitation of current models, both for parameterisations within the models and input data, is the use of empirical formulations with only regional validity, derived from in-situ experiments that are difficult to extrapolate in space and time to other geographical and climatic conditions. Together with an improvement in current model formulations, the expectation from the land community for future Earth-observation techniques is mostly based on the provision of new quantitative information that can be directly used as input to the models without going



Forest-cover map for the year 1997, produced using three input images: ERS-1/-2 Tandem InSAR Coherence, ERS-2, and JERS-1 Intensity. It demonstrates the validity of radar techniques for forest assessments. The map is one of 96 operationally produced biomass products that cover a 1 million sq km area of high-value timber in central Siberia, which experienced severe forest fires in 2003. These maps help in estimating the amount of carbon released to the atmosphere.
Credit: Schmulius/EC Contract ENV4-CT97-0743



The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) is an indicator of the state/productivity of vegetation, representing the fraction of the solar energy absorbed by vegetation and therefore driving the photosynthetic process. FAPAR can be derived from Envist MERIS data, offering the opportunity to assess and monitor vegetated land surfaces around the globe.

The upper image is an anomaly map illustrating the effect of droughts in various regions of Europe in March 2005: The vegetation activity was lower (red) or higher (blue) compared to a normal year (average for the same month between 1998 and 2002). The images below show the representative FAPAR values for May 2003, 2004 and 2005, highlighting the differences in timing of the onset of vegetation activity between these three years. Here the red regions correspond to agricultural zones for which there is high photosynthetic activity and therefore vegetation productivity, while yellow to white areas indicate a low degree of photosynthetic activity during this month.
Copyright: ESA, processed by N. Gobron, JRC

through empirical reformulations from the measured quantities to the actual model inputs. A more direct and quantitative link between observables from space and inputs needed by the models requires new observational techniques as well as more sophisticated ways of analysing the data. The predictive character of land models is necessary in order to fully couple surface and atmosphere in global climate models.

Observations

The key contribution of satellite remote sensing to the terrestrial aspects of global change is to provide a macroscopic view of the state of the geosphere–biosphere system and to monitor its time variability and evolution. After three decades of effort a substantial record of survey and monitoring data exists. However, the continuous coverage in time and space is sometimes interrupted or even incomplete, and the quality and characteristics of the acquired data often do not meet the user requirements, since in many cases they have been obtained from instruments designed for other purposes. Consequently, high-quality data from dedicated space missions are needed to complement existing and planned in-situ, airborne and space-borne observations. Research on system dynamics and interactions requires long time series, allowing one to capitalise on space observations through continuity and synergy between observation systems, providing a global view of long-term changes in ecosystem behaviour. Also, improved multi-source standardisation is required for higher level, quality-ensured land-surface data products.

Systematic observations are needed to improve our understanding of the effects of human activities on the terrestrial environment. Synergy between different observation techniques must be understood in order to monitor different ecosystems and disturbances due to climatic and environmental changes. Beyond creating a broad picture of the state of the whole land surface, future monitoring systems must also emphasise regional changes and must support regional sustainable management. The focus must be on observables that can be quantitatively characterised by space measurements, covering the range of spatial and temporal resolutions needed to address the scaling issues from local measurements to global modelling. Such scaling aspects are a key element for the study of land-surface processes in an Earth System approach.

Hence future observational priorities are:

(a) Carbon: three-dimensional biomass structure, its activity and status as well as the temporal and spatial dynamics of vegetation.

(b) Water storage through observation of the extent and level of water bodies, such as rivers, lakes and wetlands, but also soil moisture, including permafrost, snow cover, horizontal and vertical water fluxes, water quality and temperature of aquatic ecosystems, and hydrological quantities.

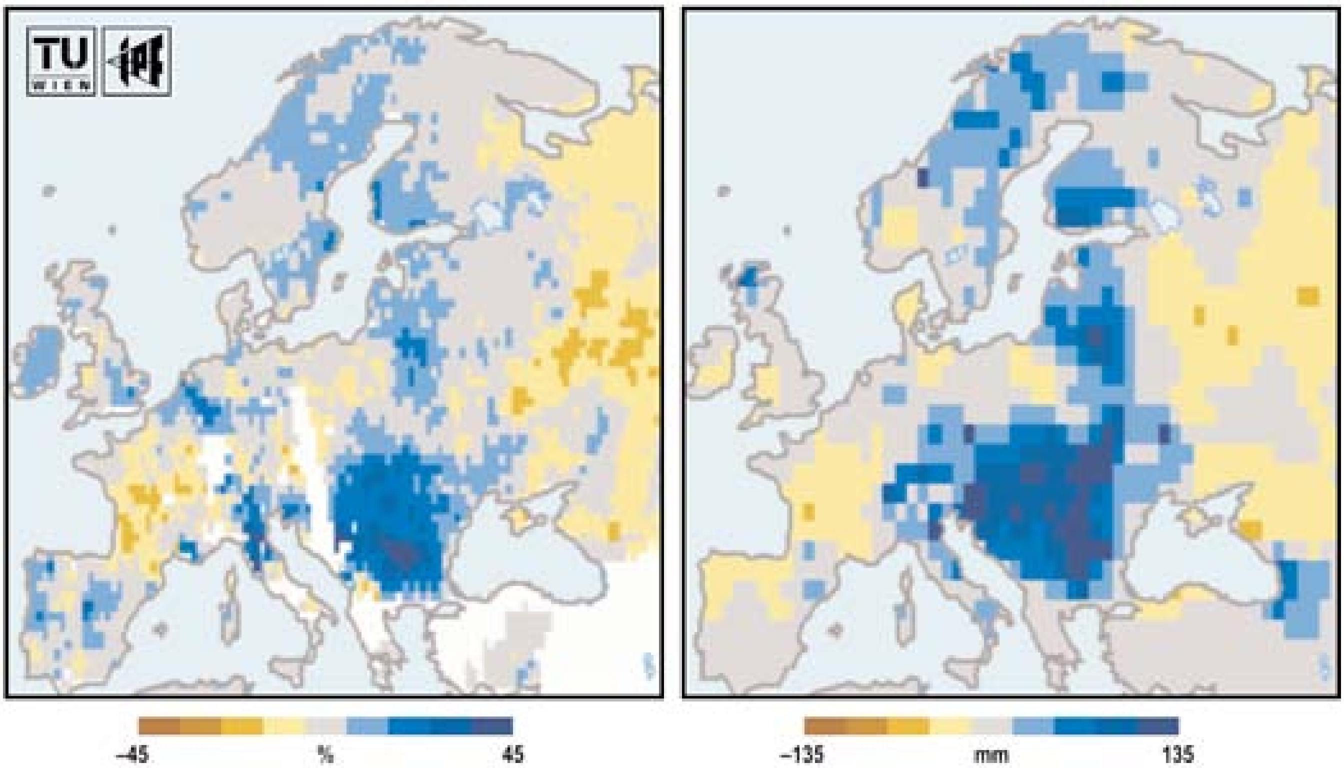
(c) Ecosystem characteristics like extent, physical structure, patterns and phenology, biome types, land-cover and land-use characteristics, as well as identification and monitoring of reactions to major natural and anthropogenic disturbances, like fires, insects and droughts.

(d) State and dynamics of human population, its interactions with the terrestrial environment, including settlements, spread of urban and large engineering infrastructures, exploitation of natural resources, land use and land management and their relation to population health and vulnerability.

Since the terrestrial geosphere–biosphere processes are interlinked through the bio-geochemical cycles, the water and energy cycles and the structure and function of ecosystems, an integrated observational strategy is required to quantitatively understand the links on a variety of spatial and temporal scales. Extreme events, for example wildfires, floods and storms, and human interference,

Image showing the variation of land surface temperature (LST) over the UK and northern France using data from the Advanced Along-Track Scanning Radiometer (AATSR), acquired from the night-time overpass on 16 July 2005. Many regions where the higher LSTs occur correspond to major cities, such as London, Birmingham, Bristol and Paris. The Thames and Seine rivers can also be seen in the image. LST data are not available over much of the northern part of the UK, as the land is largely covered by cloud (grey-scaled), blocking the instrument's view of the surface.

Credit:S. Good, University of Leicester, UK



During August 2005 heavy rainfall affected areas of central and eastern Europe, with floods reported in Bulgaria, Romania, Hungary and Macedonia. One of the hardest hit areas was Romania, with precipitation peaks up to 5 times more than average and 31 flood-related fatalities. The left image shows soil-moisture data derived using measurements from the ERS Scatterometer. The soil-moisture anomaly measured as a percentage of the long-term mean clearly emphasises the extent of the region affected. The persisting drought conditions in parts of western Europe are also visible in the image. For comparison purposes, the right image shows the precipitation anomalies for the same period observed with rain gauges.

Credit: W. Wagner, TU Wien-IPF

can cause rapid changes in ecosystem structure, and have a significant effect on vegetation regrowth and eventual changes in climax vegetation distribution.

The development and provision of instruments capable of ensuring sustained and improved observations of key geo-biophysical quantities that characterise the state of the terrestrial geosphere–biosphere system and its evolution has priority. A scientific programme leading to the development of more appropriate and accurate Earth System models, which combine geosphere–biosphere processes and surface/atmosphere interactions well identified on each scale and unambiguously related to the quantities measurable from space, must be pursued. On-going efforts, by using existing systems in high and low resolution, must continue to keep records of land-use and land-cover changes sufficiently extended in time to allow analysis of such changes associated with disturbances. Data continuity must be guaranteed in order to keep historical records, but archived time series should be re-processed using the newest algorithms to extract optimum information about trends and cycles from such historical records.

A balance between innovation through new technologies and new observables and data continuity must be pursued. While new methodological approaches and the exploitation of technological advances can lead to improved measurement accuracy as well as new types of information, such developments must also be used in the context of existing time series to establish long-term variability and to detect long-term trends at the scales relevant to Earth System processes.

System Approach

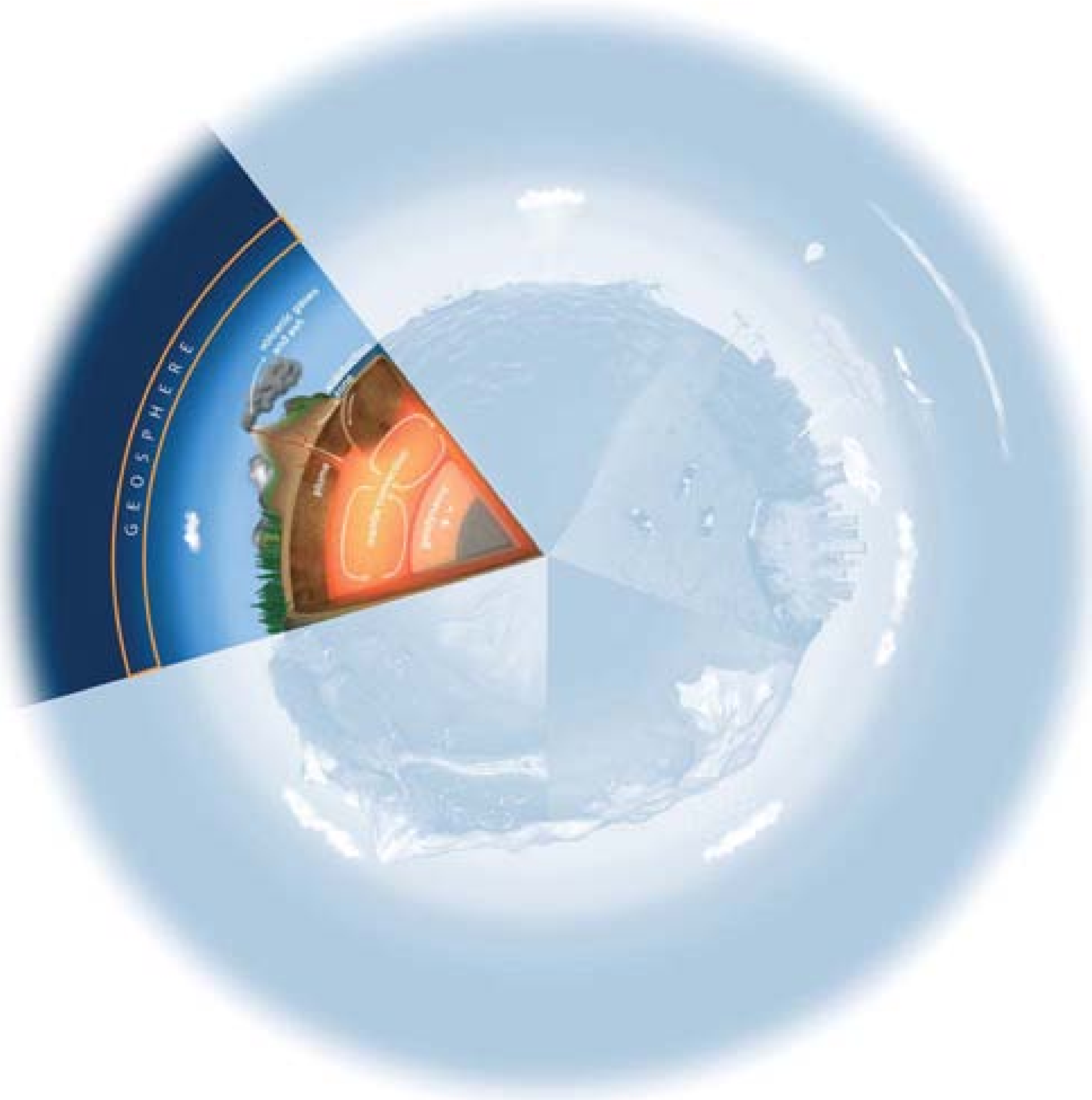
Strong links and feedbacks between the land surface and the other components of the system have to be considered. In particular, the fluxes originating from and to the land surface in interaction with the atmosphere, ocean, and cryosphere as well as the role of terrestrial ecosystems exchanging water, carbon and energy fluxes with the other components of the Earth System will require attention.

Land is a major source of energy, water and trace gases for the atmosphere, and with river runoff carbon, nutrients, sediments and pollutants enter the oceans. The land, land-surface processes and human activities are strongly inter-linked. Humans have substantially altered land-cover types, ecosystem structures, and natural habitats, often resulting in a significant fragmentation of the landscape. Human activities to extract resources from the land have reduced the ability of the Earth System to deliver ecosystem services. There should be a combined effort to measure, analyse and model the Earth System, including component interactions, thus permitting the quantification of the anthropogenic impact on the atmosphere, oceans, cryosphere, solid Earth and land.

To better understand the interaction between the land surface and other components of the Earth System, the various feedbacks also need to be investigated using coupled models that can properly address the linkages and interactions. Advances in understanding land/atmosphere exchange can be made through better representation of terrestrial ecosystem state and dynamics in atmospheric models at all scales, from local to global. The link between land surfaces and the cryosphere is largely governed through permafrost changes that influence biochemical processes, and through snow cover impacting the hydrological cycle and its resources. The oceans are influenced mainly by run-off from the land and specifically by anthropogenic impacts on the land side of the coastal zone. Finally, the interaction between the land, ocean, cryosphere and atmosphere is also influenced by solid-Earth processes, e.g. direct volcanic injection of greenhouse gases into the atmosphere.

A long-term goal is the routine assimilation of remotely-sensed land-surface data into Earth System models, both for diagnosis and prediction. Rapid developments in land-surface data assimilation are anticipated and attempts to incorporate satellite- and ground-based observations within a land-surface modelling framework should be encouraged. Progress requires improvements in models, space-borne observations, in particular the delivery of long time series of products with accompanying error characterisation, and the joint use of space-based and in-situ measurements at appropriate scales. This latter includes recent initiatives to integrate networks of in-situ sensors with space-borne observations in near-real-time.

Strategic and timely observations of critical Earth System processes and states are a central feature of the new research approaches, and a sound collaboration and coordination between the global environmental change research programmes and space agencies is essential for success in optimising the use of Earth Observation information for a broader understanding of the Earth System.


GEOSPHERE

4.5 Solid Earth

State of the art

A fundamental constituent of the Earth System is the 'solid Earth', composed of the inner core, the (liquid) outer core, the lower and upper mantle, and the crust. We know from observation that the Earth's magnetic and gravity fields, its shape, rotation, and deformation all change on a wide range of spatial and temporal scales in response to a complex set of processes acting in its interior. However, our knowledge of the structure and composition of the Earth's internal layers – and of the dynamics of their interactions with each other and with the atmosphere, hydrosphere, and cryosphere – is still incomplete in important respects. Understanding these processes within the solid Earth is a necessary requirement for understanding the Earth System as a whole.

The tectonics of the Earth's lithosphere, its strong outer layer, drive processes that have major impacts on humankind. The energy released by earthquakes and volcanoes, and their direct consequences such as tsunamis, landslides and liquefaction, cannot be contained by human actions, and the increasing pressures of a growing population are producing new centres of habitation in regions at greater risk from natural disasters. As these centres proliferate, the impact of such events will have increasingly serious consequences. There is an urgent need to systematically monitor such regions, in order to improve prediction of the spatial and temporal distribution of disasters, and hence mitigate their consequences for society.

Processes in the Earth's deeper interior also influence the environment in which we live. Global and local patterns of relative sea-level change are intimately connected to surface motions of the solid Earth. The combination of regional ice melt and rebound of the Earth's surface following de-glaciation induces complicated patterns of global sea-level change, while tectonic activity causes cyclic and permanent changes in surface elevation. These changes must be understood before adequate protective measures and medium- to long-term planning can be undertaken. Large-scale tectonic motions, such as rearrangements of plate geometry and the uplift of mountain ranges, change the boundary conditions for the oceans and atmosphere; investigation of these influences offers the opportunity for improved understanding of the climate system. Convection in the mantle generates fundamental sources and sinks for the cycling of elements in the environment, for example at volcanoes, oceanic ridges, and subduction zones. Hydromagnetic convection within the core sustains the Earth's magnetic field and magnetosphere, which shield life from the high-energy particles in cosmic rays, and the atmosphere from being directly exposed to the solar wind. Understanding of all these systems requires the improvement of our knowledge of the physical properties of the Earth's interior.

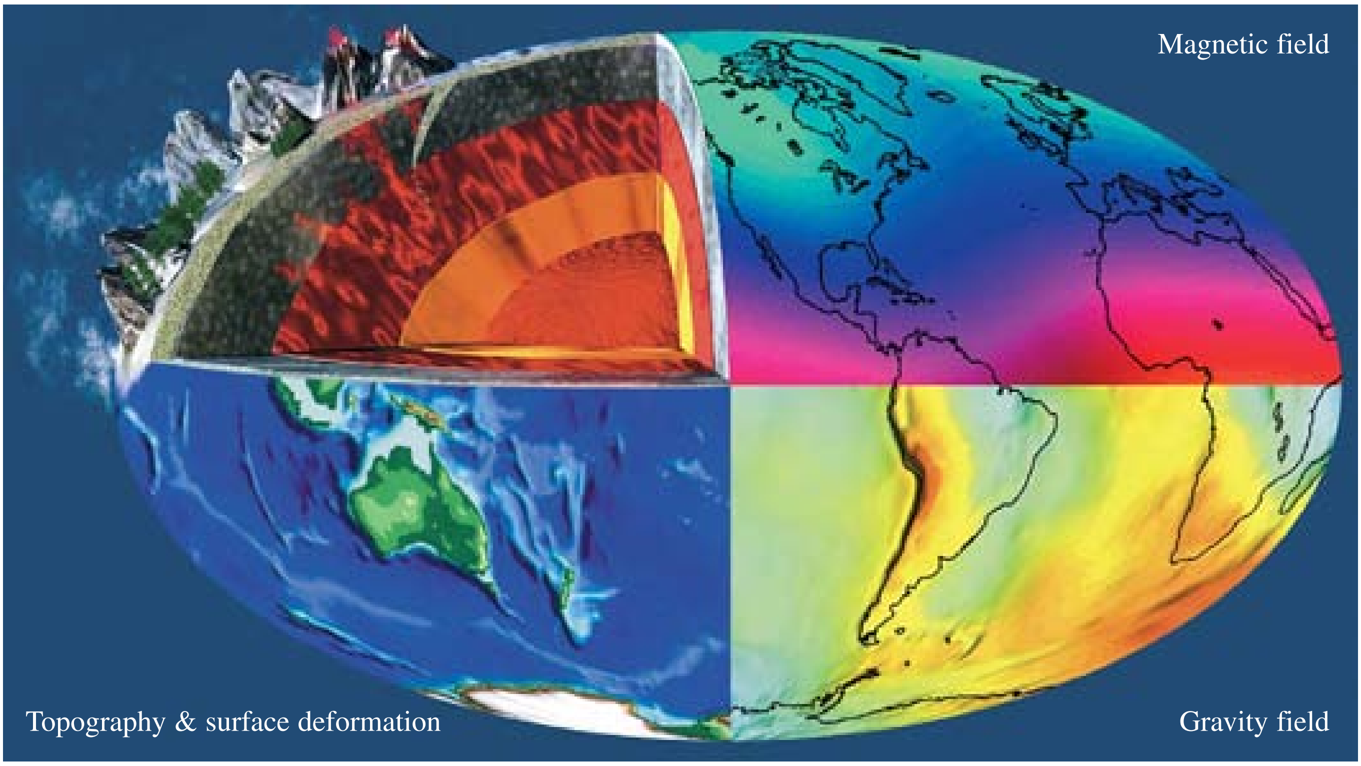
Our current understanding of solid-Earth processes is built on a combination of ground- and space-based measurement strategies. Recent advances in seismic tomography provide views of the Earth's interior on scales of a few hundred kilometres; these data, supplemented by high-pressure and high-temperature laboratory measurements, provide information about mechanical bulk properties. At the same time, satellite missions (already flying or being developed) add a scale of observation that cannot be achieved at the Earth's surface. Gravity missions, combined with geological, seismological, topographic, bathymetric and electromagnetic data, provide information about interior properties; magnetic-field-measuring satellites allow, in combination with aeromagnetic surveys, global compilations of detailed lithospheric fields to improve the understanding of plate tectonics in the oceanic lithosphere, and to identify lateral variations in heat flux. Space- and ground-based data on the time-variable deformation of the Earth's surface, combined with the seismic and geological record, have provided important insights into the causal dynamics of tectonic activity.

Challenges

The solid Earth is a unique component of the Earth System in that its governing processes have fundamental time scales that range from seconds (earthquakes) to hundreds of millions of years (mantle convection cycle). Existing data sets are currently too short to illuminate all but the shortest of these time scales, and it is important that the Earth Observation and 'ground-based' solid-Earth communities should communicate effectively with one another.

The major challenges facing the solid-Earth observing community remain those of improving and optimising global data sets, to gain an improved understanding of the solid Earth and the dynamic processes acting in the core, mantle and lithosphere, such that we may develop a reliable predictability that may one day be used to mitigate the impacts of solid-Earth processes. In addition, precise estimates of mass variations in the atmosphere, the oceans and the cryosphere would allow us to separate changes in the Earth's gravity arising from solid-Earth effects from those driven by changes in the other components of the Earth System.

Information that can be acquired from space that is relevant to the Solid Earth and Earth System Science.
Copyright: ESA/Medialab



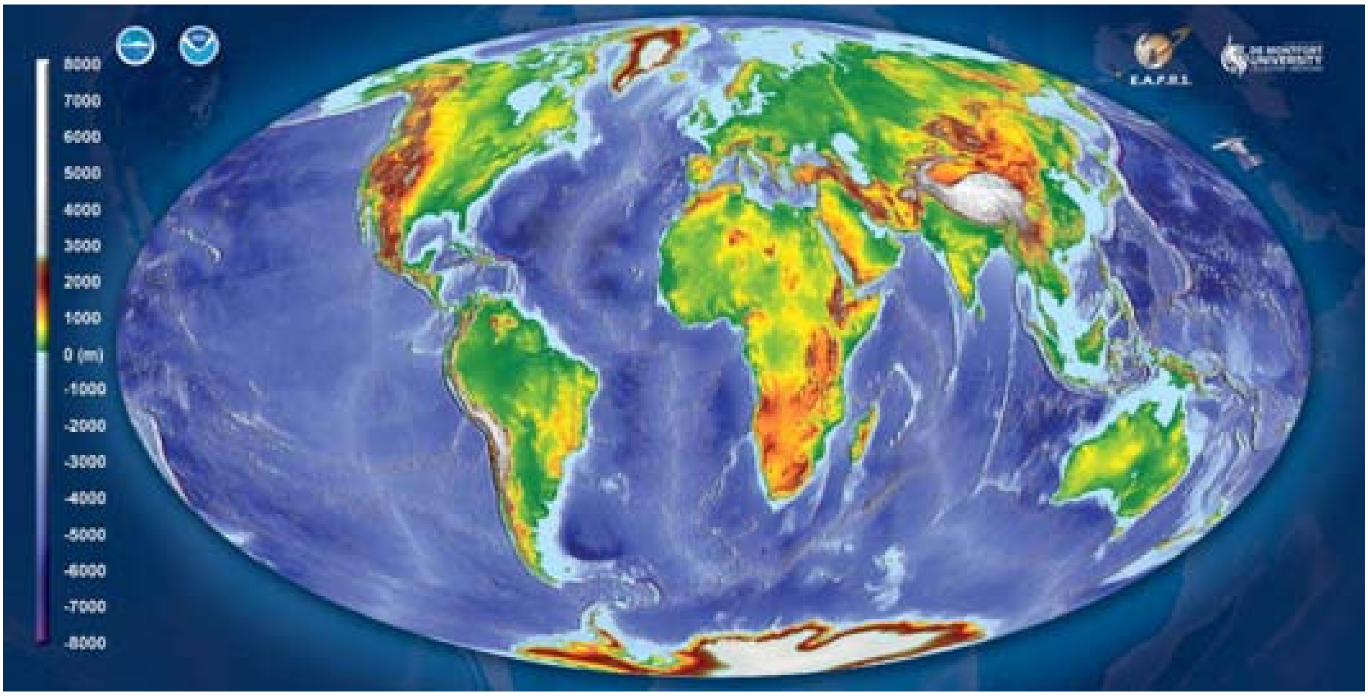
Key scientific approaches to learning about the solid Earth's composition and geodynamic processes are:

- observations of external potential fields that provide insight into the current state of, and the changes occurring in the Earth's interior

- observations quantifying the deformation of the Earth's surface.

Faults within continents are much more difficult to detect than those at plate boundaries – and there are many more of them. About 2 million people were killed in the past 200 years by earthquakes. Three of these events each caused over 200 000 deaths, and several others were in the 100 000 range. With the growing population concentrations in areas with a high risk of earthquakes, it is only a matter of time before the first mega-death earthquake occurs. Radar interferometry can produce maps of ground deformation over regions hundreds of kilometres across, with a horizontal resolution of a few tens of metres. This capability has transformed the way in which deformation of the Earth's surface is studied. It is now possible to measure the slow deformation in between earthquakes and hence obtain the rate of strain accumulation within a region – allowing policy makers to obtain reliable estimates of the seismic hazard, to make informed medium-to-long-term decisions about the location of new population concentrations and major infrastructural works, and to plan for emergency responses to, and mitigation of, highly destructive earthquakes.

Radar interferometry is already being used to monitor the activity of some volcanoes, though the available data coverage is not good enough for systematic global monitoring. In another application, interferometry can be used to monitor subsidence caused, for example, by the extraction of oil or



Global topography and bathymetry measured by space-based radar altimetry.
Credits: ESA, using bathymetry data courtesy of: W. Smith, NOAA Geosciences Lab., USA, and D. Sandwell, Scripps Institute of Oceanography, USA, and altimeter-corrected elevations from P. Berry, DeMontfort Univ., UK

ground water. Adequate observation from space can help to unify local land-based monitoring systems and can serve as a control tool for the modelling of ground deformation due to tectonic, volcanic, or other processes.

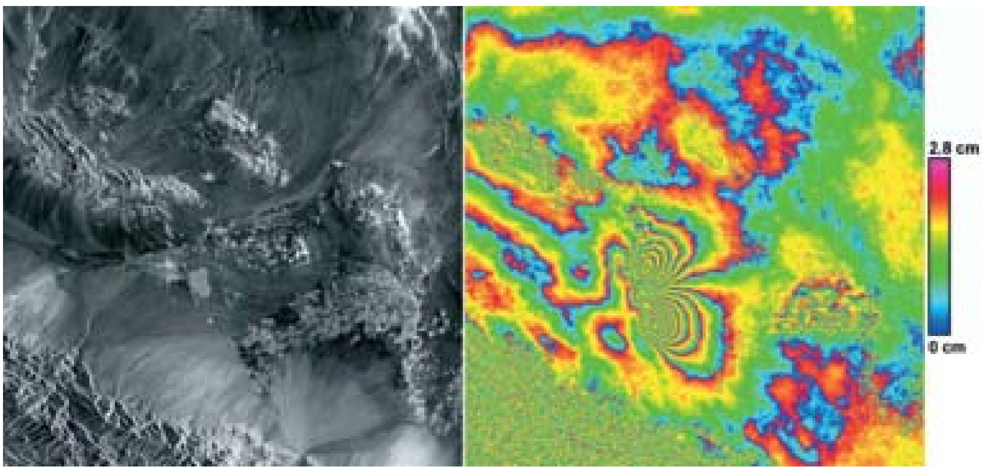
New, existing, and planned satellite measurements will enable us to measure potential fields with increased precision and resolution, as well as detect relatively rapid variations in these fields, opening the door to a new set of science applications, many of them interdisciplinary in nature. These developments make it possible for the first time to perform synoptic-scale measurements on fundamental processes that involve both the interior of the Earth and surface processes, such as circulation of the oceans and atmosphere or changes in ice cover and the associated sea-level variations.

Future observations should be designed to capture not only the movements of the oceans and atmosphere, but also have the potential to detect tectonic changes on time scales of days to months. Such improvements would lead to more accurate models of mass distribution and mass transport in the geosphere system, and would open the way for geophysical contributions to understanding mass movements in the other Earth System components. For example, gravity measurements have been instrumental in observing mass variations in the ocean, the cryosphere and continental waters. Combined with other information, gravity data would lead to a better understanding of core processes and their possible impacts, for example on the shielding of the atmosphere from charged particles, or on the Earth's rotation.

The ultimate goal of the solid-Earth observing programme is to develop a reliable predictive capability that can one day be used to mitigate the impacts of solid-Earth processes on the human population.

Observations

Surface observations have a key role to play in monitoring the seismic cycle, the build-up of volcanic hazards, and other instabilities of the land surface. A dedicated programme of observation of tectonically active regions of the Earth's surface is needed, both for the urgent problem of assessing seismic and volcanic hazards, and in order to gain insights into the physical



On 26 December 2003 an earthquake (Ms = 6.6) shook a large area of Kerman province in Iran. The epicentre of the devastating earthquake was located at 29.01°N/58.26°E. ESA acquired Envisat radar data before and after the quake. Using three descending-pass data sets, acquired on 11 June and 3 December 2003 and 7 January 2004, a differential interferogram (right) was generated showing the displacement changes in the satellite direction (LOS). Every repetition of the full colour interval represents a LOS (line of satellite) change of 2.8 cm. The maximum relative movement is about 48 cm, near the city of Bam. The left figure is the radar intensity image centred on the city of Bam.

Credit: Xia Ye and H. Kaufmann, GeoForschungsZentrum Potsdam, Germany

The Challenges of the Solid Earth

Challenge 1: Identification and quantification of physical signatures associated with volcanic and earthquake processes – from terrestrial and space-based observations.

Challenge 2: Improved knowledge of physical properties and geodynamic processes in the deep interior, and their relationship to Earth-surface changes.

Challenge 3: Improved understanding of mass transport and mass distribution in the other Earth System components, which will allow the separation of the individual contributions and a clearer picture of the signal due to solid-Earth processes.

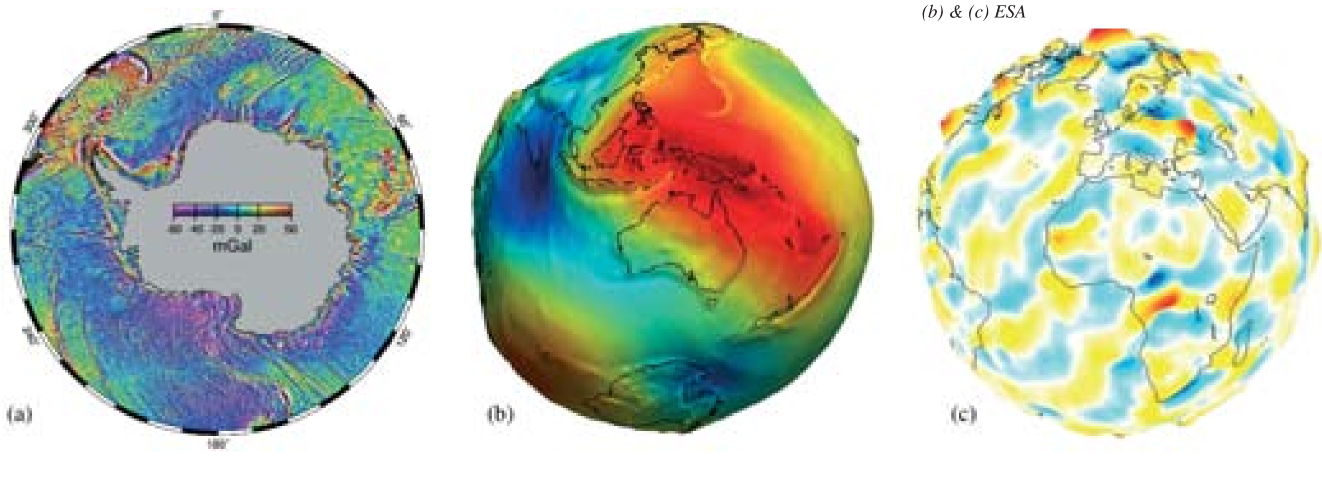
Challenge 4: An extended understanding of core processes based on complementary sources of information and the impact of core processes on Earth System science.

Challenge 5: The role of magnetic-field changes in affecting the distribution of ionised particles in the atmosphere and their possible effects on climate.

mechanisms of these processes, which are still poorly understood. Linkage between surface change and potential field change could provide additional insight and, particularly in the case of volcanic emissions, there are strong links to atmospheric processes.

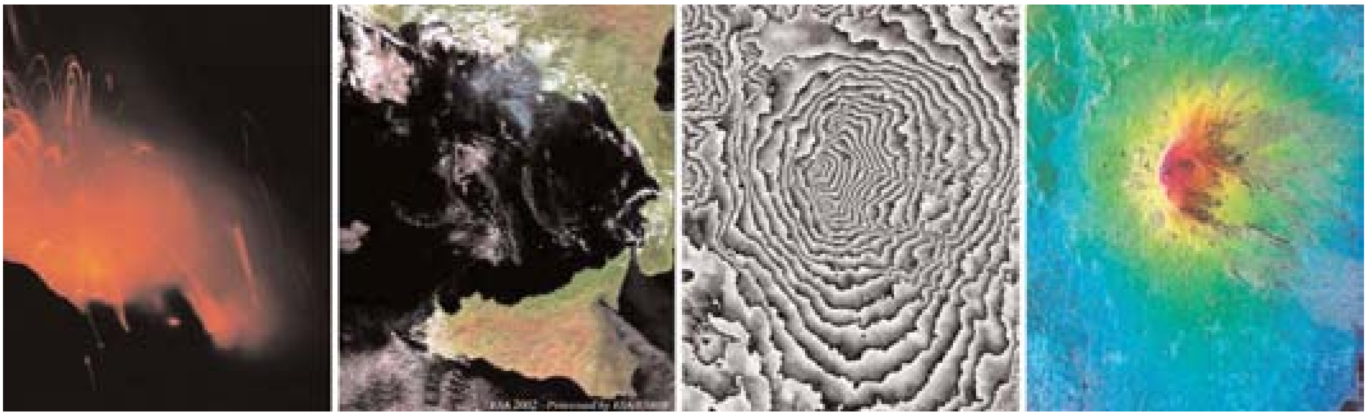
Global monitoring of continental-scale movements is presently implemented within the International GPS Service, but with reasonable resolution in only limited parts of the World, usually in the economically most developed countries. Ground-based measurements are therefore critically dependent upon remote-sensing observations for a full understanding of geophysical signals, because of the ability of remote sensing to make synoptic-scale measurements at high resolution. In the less-developed, and often more isolated, countries remote-sensing observations are the only realistic means of assessing hazards. In all regions, remote sensing of surface deformation adds immeasurable value to the ground-based observations.

Detection of surface deformations may rely on a number of different techniques, the most important of which will be interferometric synthetic-aperture radar for high-precision digital-elevation data, measurement of land-



Fine structure of the marine gravity field from ERS satellite altimetry (a), the gravity field as expected from GOCE (-100 m to 70 m from blue to red) (b), and the crustal magnetic field as expected at Swarm altitude (-15 nT to 15 nT from blue to red) (c).
Credits: (a) D. McAdoo, NOAA & S. Laxon, UCL; (b) & (c) ESA

(a) (b) (c) (d)



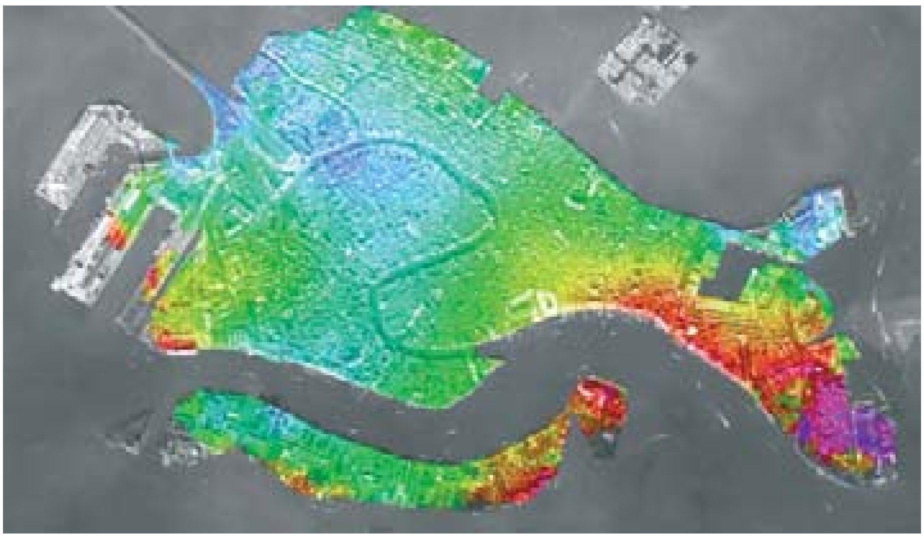
Eruption of the Mount Etna volcano in Italy, in July 2001. Shown are the actual eruption, a Landsat-5 TM image, a black and white fringe image and an elevation model.

Credits: (a) & (b) ESA; (c) & (d) H. Kaufmann, GFZ, Potsdam

surface response to tectonic and volcanic activity, assessing subsidence and land-slide hazards, and improved prediction of flood hazards. Preferably, such a future capability should aim at capturing full 3D-deformation as an improvement over existing capabilities. Radar and laser height measurements from satellites may also be useful complements. In addition, rapid growth of ground-based measurement activities, particularly continuous GPS measurements, can be expected.

Structures and processes in the Earth's interior can be detected at satellite altitude by their contribution to the external potential fields of the Earth, the gravity field and the magnetic field. For the latter, the recently proposed Swarm mission will lead to a dramatic improvement in existing models. This improvement specifically derives from the better distinction between the spatial and temporal variations of the geomagnetic field, by the use of a constellation of spacecraft. Future concepts may need other dedicated space-time sampling scenarios tailored to future mission objectives.

A constellation of satellites with interlinking laser interferometry also seems to be a possible means for studying, via gravity variations, the mass transport and distribution in the Earth System, in combination with other information. Other techniques can also be considered, such as gravity gradiometers and



Subsidence map of the city of Venice, showing up to 2 mm per year (purple) of subsidence over the period 1992-1996

Credit: GAMMA/ESA

atomic clocks, but only when sufficient performance can be achieved. If the system were sensitive enough, it could even observe core dynamics, as a complement to magnetic-field measurements.

System approach
With modern satellite-based observations of the Earth, the long-held vision of observing the global pattern of change from space is now within reach. This marks a tremendous advance in the way we investigate the Earth System. In particular, the move from 3D to 4D observations, from a focus on properties to a focus on processes, and from the analysis of individual components to the analysis of interactions between systems, opens the way to a new era in understanding the dynamics of planet Earth.

Recent and planned satellite missions provide images, with unprecedented spatial resolution, of changes in the Earth's gravity and magnetic fields, in the Earth's orientation and rotational motion, in active surface deformations of the continents and ice sheets, in the distribution of water in the atmosphere, and in global oceanic water flow and bottom-pressure changes. These observations provide integrated insights into processes as diverse as solid-Earth dynamics, ocean circulation, melting of ice sheets, changes in the hydrologic cycle and climate change, and – more significantly – into the coupling between these individual components, which is essential for a deeper understanding of the Earth System.

Satellites measure a complex signal whose components have to be attributed to different Earth System components. This needs in-situ data and models and a coherent strategy for calibration procedures, and the use of independent data for validation, refinement and the separation of effects. This requires continuity of data series, their interlocking with the longer time series from ground-based observations, which are often sparse and may be in proxy form. An additional demand on the remotely sensed data is that there must be internationally standardised procedures for their exchange, and a processing capability for near-real-time use.

The ultimate goal is a coupled Earth-System model that conserves energy, mass and momentum on a variety of spatial and temporal scales, but this goal must be approached through the assembly and linking of reliable knowledge about the workings of individual components of the system. This task requires not only a huge research and observational effort to model the individual components, their key state variables and their evolution, but also missions that target key areas of coupling within the system. A multi-disciplinary effort to combine and complement space-borne sensor data, with airborne data, ground-based measurements and laboratory-derived quantities is crucial for improved understanding, modelling and prediction.

5 The Wider Context

From the outset, ESA's Living Planet Programme had the ambition to facilitate international cooperation and utilise existing facilities and competences within the ESA Member States and Canada. This cooperation takes several forms, from direct cooperation on the implementation of specific missions, through joint science activities in connection with ESA's and other agencies' missions, to interaction with international scientific research programmes, in order to ensure that ESA's activities have an optimum impact from a global point of view.

European assets for Earth System Science

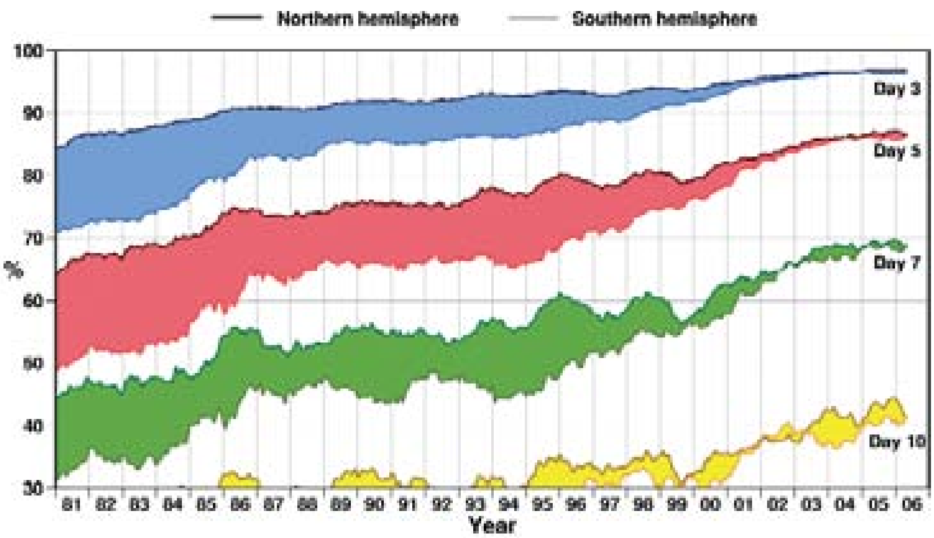
Over the years, European countries have developed a strong leadership in Earth System Science. The development of fully coupled Earth System models is well underway at the Hadley Centre and the University Global Atmospheric Modelling Programme (UGAMP) in the United Kingdom, at the Max Planck Institute for Meteorology in Hamburg, Germany, and at the Institut Pierre Simon Laplace and Meteo-France in France, to cite but a few. Many other European organisations are working in the same direction. Europe also holds a strong position in other key areas of Earth System Science, such as oceanography and glaciology. Furthermore, several European organisations with an interest in Earth System modelling have grouped together within the European Network for Earth System Modelling (ENES).

The development of a common software infrastructure for European Earth System models will progressively reduce the duplication of technical work and allow the community to concentrate on the important scientific questions underlying the formulation of the component models. The Programme for Integrated Earth System Modelling (PRISM) project of ENES has taken important steps in this direction by sharing the development of mathematical links between the various components of the Earth System, management of scientific codes and of large archives of numerical experiments, the interfacing with common observational databases, the facility to monitor and supervise complex suites of numerical experimentation. Links are currently being developed between this European ENES initiative and the similar Earth System Modelling Framework in the USA.

Earth System models are developed through a complex and systematic process of comparison with observations at the relevant scale. Systematic differences between model simulations and observations, called 'biases', point to the incorrect representation of some process that must be improved in the models, or to systematic observational errors that must be corrected. Once the biases are reduced to a minimum, the remaining random differences between the models and the observations can be exploited to further improve the model's formulation, or to create a set of model variables representing the reality at a specific point in time. The model can then be used for predictions. This whole process is called 'data assimilation' and lies at the heart of Earth System Science. Europe has developed a very strong leadership in pioneering the variational approach to data assimilation. This approach was first successfully developed in meteorology, where the European Centre for Medium-Range Weather Forecasts, together with partner European meteorological centres, has acquired an undisputed lead.

Similar data-assimilation techniques are now common in oceanography, and are developing quickly in atmospheric chemistry and in the land-surface science. Europe has many assets with which to retain global leadership in all aspects of Earth System Science data assimilation, but international competition is tough. The next challenge is to develop efficient methods for data assimilation in coupled models, including several components of the Earth System models. For instance, coupled atmosphere–ocean data assimilation will be necessary to develop accurate seasonal and decadal predictions of climate anomalies. Coupled atmosphere and land-surface data assimilation will be necessary to evaluate reliable global soil-moisture time series, since this quantity is very difficult to observe from space. Coupled data assimilation for weather and atmospheric composition will be tried in the Global Environmental Monitoring from Space (GEMS) project.

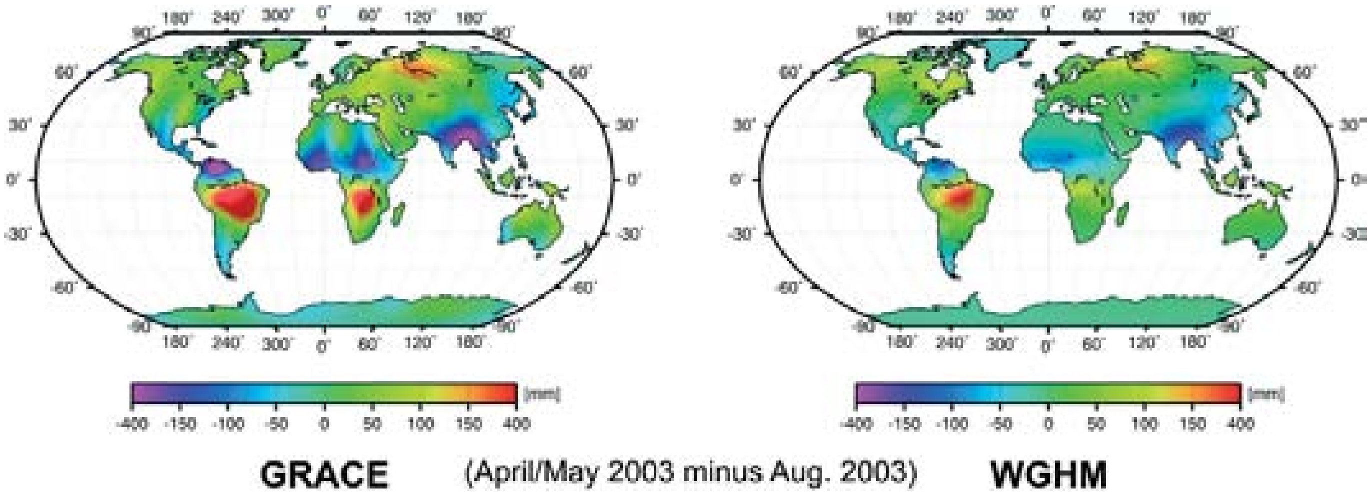
Data assimilation opens the way for optimised state analyses, and subsequently more reliable prediction of the state of the Earth System and for re-analyses. Re-analyses are long time series of historical Earth System data obtained from state-of-the-art data assimilation systems and all available observations. The ECMWF has led the meteorological community in the creation of the initial concept of re-analysis by performing several multi-year re-analyses of the dynamical and physical states of the global atmosphere. The most recent of these projects, ERA-40, has allowed the production of a 45-year (1957-2002) time series using all available satellite and surface-based observations of the physics and dynamics of the atmosphere, plus some satellite observations of ozone. In parallel, some steps have been taken towards re-analysis of the state of the ocean for the last 20 years (e.g. the ENACT project). Future re-analysis projects will encompass several components of the Earth System, and attach high priority to capturing the climatic trends over the last 100 years, for which a reasonable observational database exists. In the not-too-distant future, the Earth Sciences community will have the capacity to produce coupled re-analyses of the Earth System, including weather, atmospheric composition, state of the ocean, amount of moisture in the continental soils, hydrology of large rivers, and the state of the biosphere and cryosphere. This, in turn, will open the way to an objective verification of the predictional capacity of Earth System models. Europe has



Increase in anomaly correlation of 500 hPa height forecasts, to a large extent due to assimilation of satellite data.

Credit: ECMWF

the capacity to accomplish the first comprehensive re-analysis of the entire Earth System if all of the relevant European organisations work towards a common goal.



Geographical distribution of differences over continents between GRACE satellite gravity-field solutions and those predicted by the Water GAP Global Hydrology Model WGHM (in mm of equivalent water column); averaging radius 750 km.
Credit: GeoForschungs Zentrum, Potsdam

In the context of the Priority Research Programme of the German Research Association DFG, a large programme has been started on investigating existing capabilities for studying mass transport and mass distribution in the Earth System. This is a multi-disciplinary effort aimed at exploiting current satellite mission with complementary data types for the comprehensive separation and modelling of individual contributions related to the solid Earth, oceans, cryosphere, atmosphere and hydrosphere. Beyond better process understanding, this attempt will probably lead to improved Earth System modelling capabilities and requirements for future observational components. In this context, the consistency of reference systems and corrections to the different types of observations play an important role. This is one of the aims of the Global Geodetic Observing System (GGOS) initiative that is a natural link to GEO and IGOS.

The final step in the integration of Earth System Science is the definition and operational delivery of services to society. The GMES initiative by ESA and the European Commission has popularised the opportunities currently offered by Earth System Science to serve societal needs, and has the creation of a sustained organisation for services to society as its objective. This requires continuous observations of the Earth System, quality coupled modelling and data-assimilation systems, and a set of application models to translate the analyses and forecasts into variables of direct interest to the users, such as air and water quality at a given location, water resources in a given area, expected food production over the next growing season, early warnings of environmental risks, etc. International collaboration on a grand scale is absolutely necessary to achieve these ambitious goals, and this was recognised with the recent creation of the Global Earth Observation System of Systems (GEOSS). GEOSS is targeting international cooperation taking into account all sectors of Earth Science. GMES is the European contribution to GEOSS, and the European Earth Science community must strongly contribute to to the optimisation of this global approach. The GEO has identified nine societal benefit areas for Earth Observation: Disasters, Health, Energy, Climate, Water, Weather, Ecosystems, Agriculture including Fisheries, and Biodiversity.

The development of Earth System Science and the related services to society must be supported by an appropriate policy for the wide exchange of data between the interested communities. In much the same way as the meteorological sector has established widely accepted rules allowing for the extensive real-time exchange of key data for weather prediction throughout the World, other Earth Science sectors must now increase the international circulation of key datasets to allow quicker development of Earth System Science and the related services to society.

Cooperation on mission implementation
Direct cooperation on mission implementation has been undertaken both with ESA Member States and with other partners. This allows the programme to build on specific expertise and draw on additional available resources. It is also a way of keeping the mission costs to ESA within the agreed limits. Examples of missions of this kind are SMOS and EarthCARE. Although not implemented yet, the concept of joint calls for mission proposals together with other agencies has been agreed, and could take the form of completely joint missions or instrument contributions to the mission of a given agency.

Scientific team cooperation
For missions under development, interaction between scientific teams on a global scale is strongly encouraged. In many cases, related and complementary activities are also being undertaken outside ESA, and missions can benefit from joint science activities, including for example campaigns for calibration, validation and algorithm-development purposes. In particular, programmes like the European Union’s Framework Programme enable a significant amount of scientific research to be undertaken on issues addressed by the ESA missions, often utilising data from the satellites. Similarly national research programmes may offer substantial opportunities for supporting and extending the scientific benefits from ESA’s programmes.

International research programmes
The international scientific community has organised itself into broad programmes, e.g. the World Climate Research Programme (WCRP), the International Geosphere-Biosphere Programme (IGBP) and others. These programmes are important sources of unified scientific requirements that should be taken into account when creating Earth Science satellite missions. With the current trends towards a system approach, these programmes are strengthening their links and are undertaking cross-programme activities that involve several of the players. It is important for ESA to have good connections to these programmes in order to collect their requirements and to make them aware of the Agency’s plans for future activities. Cooperation with WCRP and IGBP has been strengthened in recent years, and this should be continued.

Global initiatives
An important benefit of Earth Science satellite missions and other activities is

the well-established potential they provide for the development of new Earth Observation applications, the development of operational systems for meteorology being a prime example. Other areas are also progressing, and political decisions like international treaties on, for example, ozone and carbon, emphasise and formalise the need for related applications.

The link between science and applications works both ways. On the one hand, scientific progress forms the basis for the development of new applications, but operational systems also make important contributions to scientific research, particularly by providing long time-series of global data, something that is notoriously difficult to justify in research-oriented space activities. A good example in this respect are the missions of Eumetsat and similar organisations.

During the last decade, the Integrated Global Observing Strategy Partnership (IGOS-P) has formulated global observing needs for a number of themes. Other more recent developments are the Global Monitoring for Environment and Security (GMES) intiative by the European Union, ESA and other partners, and the Global Earth Observation System of Systems (GEOSS), to which GMES is Europe's planned contribution. Although these initiatives go well beyond the scientific needs, these are also included and these intiatives therefore provide a natural link between science and applications.

6 Living-Planet Contributions and Implementation Issues

6.1 Missions

ESA's primary contribution to Earth Science is the provision of data products and associated services from the Agency's Earth Observation satellites. In addition to data from its own satellites, ESA also facilitates the provision of data from other organisations' satellites where relevant.

Earth Observation satellites for Earth Science are identified, selected and developed in close cooperation with the scientific community. Identification of candidate missions or mission concepts is regularly conducted via open calls for proposals to the scientific community. In order to account for scientific areas already addressed through ESA or other missions, science priorities are defined when necessary in order to focus new proposals on issues that have maximum scientific impact. This also allows new scientific results that pave the way for new missions to be taken into consideration. Exploitation results, both from ESA and other missions, are generally used to provide ideas for new developments, both for individual instruments and complete mission concepts. Identification of the scientific priorities falls under the aegis of the Agency's Earth Science Advisory Committee (ESAC).

Promising mission concepts proposed to the Agency are subjected to feasibility studies in order to determine the maturity of the concepts before selecting them for implementation. The selection of candidates for feasibility studies is conducted with the support of the scientific community, both through the use of evaluation panels and open consultation meetings with the community at large. The final recommendations from such selection procedures are formulated by the ESAC.

Development of missions, both at the feasibility level and during actual implementation, calls for careful formulation and maintenance of the mission requirements to ensure that the scientific goals are achieved. During this process, the technical concepts are matured and trade-offs are made. The balance between these trade-offs and the scientific requirements often means that detailed analyses and study activities have to be performed. For this, the Agency relies on advisory teams from the science community in order to estimate the possible impact of such changes, in addition to formulating mitigation strategies. There are also examples where such supporting studies have led to substantial simplifications on the technical side. End-to-end simulators that can be used to analyse the impact of technical modifications on the overall system are particularly important tools.

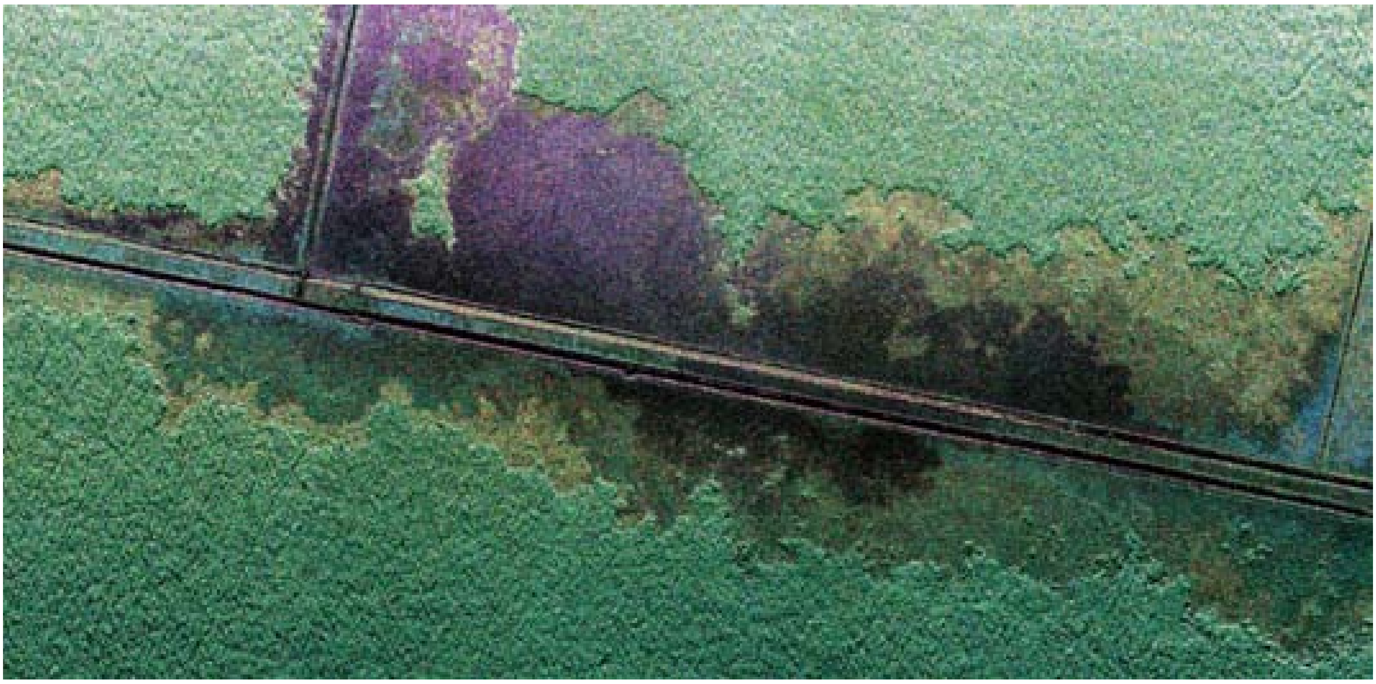
Science missions based on novel concepts or instrumentation invariably involve scientific uncertainties. During the feasibility studies, this uncertainty has to be reduced to a level acceptable to the scientific community, and this phase therefore concentrates on showing that the measurements proposed can actually be used to achieve the mission goals. This also includes the identification of any auxiliary measurements needed, either by modifying the technical concept or by using supporting measurements from other space-borne, airborne or ground-based data sources. It is particularly important to develop the processing algorithms needed in good time, in order for the ground segment to be ready by the time the mission is launched.

Airborne campaign activity and in-situ measurements of snow accumulation on the Greenland ice sheet.
Credit: R. Forsberg, DNSC

Although the Agency mainly relies on the scientific community to identify and perform the science studies, operational benefits can also often be derived from science missions. Operational entities often run large analysis systems that use data from a number of sources. It has become common practice to consider whether the data from science missions can also be assimilated into such systems. This has the potential to show the impact of the new data, and may in turn trigger further input to the scientific usefulness of a mission. A commonly used tool in this respect are Observing System Simulation Experiments (OSSE). Such use of satellite data generally requires that it be provided in near-real-time in order to be used on a regular basis.

Introducing new measurement concepts from space usually requires a stepwise approach. Airborne campaigns are regularly used both for testing the measurement concept itself, for testing the instrument technology, and also to simulate data that allows mission feasibility to be checked or algorithm development to be undertaken. The differences between space-borne and airborne measurements, such as resolution, sampling, platform stability, as well as atmospheric and ionospheric effects, need to be carefully considered when scaling up to space systems from airborne systems. During the commissioning phase immediately after the launch of a mission,

Ground measurements of forest biomass. A special 25 km-long bridge was constructed through otherwise inaccessible peat forest on the island of Borneo to support scientific studies. This bridge was used to gather extensive forest-biomass measurements for comparison with airborne radar data during ESA's Indrex-II campaign in 2004.
Credit: D.H. Hoekman, Wageningen University, NL



Together with the Indonesian Ministry of Forestry, ESA initiated an airborne radar campaign (known as 'Indrex-II') in 2004 over the island of Borneo (Kalimantan). The main goal was to identify the optimal SAR sensor configuration and related algorithms for tropical-forest monitoring and forest-biomass retrieval. This colour composite was generated from L-band radar images acquired using the DLR airborne SAR system flying at 3000 m altitude. Bright-green areas represent undisturbed tropical forest. The dark lines in the image are recently built drainage channels. The negative impact of the channels is clearly seen in the forest adjacent to the canals. The brown and purple areas are either dying forest or deforested areas.
Credit: ESA

measurements have to be calibrated. This is mainly a technical issue, but this phase is also used to undertake validation activities. Airborne campaigns are commonly used for such validation activities, and they are often maintained throughout the lifetime of a mission.

The long history of scientific-mission development in the Agency has shown that there is a strong relationship between previous mission ideas, science- and technology-related studies in the Agency, and new proposals. Usually, the number of mission concepts chosen for feasibility studies is substantially larger than the number of missions actually selected for implementation. The studies undertaken on these concepts also contribute strongly to the missions not selected, helping to further mature mission ideas and prepare the science community for making improved proposals later on. Even for missions not selected for feasibility studies, open issues are often identified that allow preparatory activities to develop these concepts further. It is therefore of the utmost importance that the Agency be able to keep a relatively broad front of issues proposed by the scientific community in order to foster this kind of incubation of ideas and concepts.

With an increasing number of Earth Observation satellites available, the concept of using constellations of more than one satellite for a specific purpose has become more common. This is linked not only to the development of smaller satellites, but also to the development of more sophisticated scientific models that are able to use different types of data. Also, synergies between different instruments on the same platform are being exploited, leading to trade-offs between orbit configurations and measurement strategies in order to optimise the use of instruments with partially conflicting requirements.

The nature of the data needed to address a specific scientific question varies from a well-defined set of measurements during a given time period, to long-term measurements of a set of parameters. The former is more easily addressed through the Earth Explorer missions, since a single mission can make a substantial impact in terms of scientific output. The latter relies on continuity of observations, where comparability of measurements over long time periods is more important than innovative measurements. This is where the role of operational observations becomes particularly important, and where the Eumetsat and GMES types of missions, although defined based on operational needs, will be able to contribute significantly to scientific development.

6.2 Science and Data Exploitation

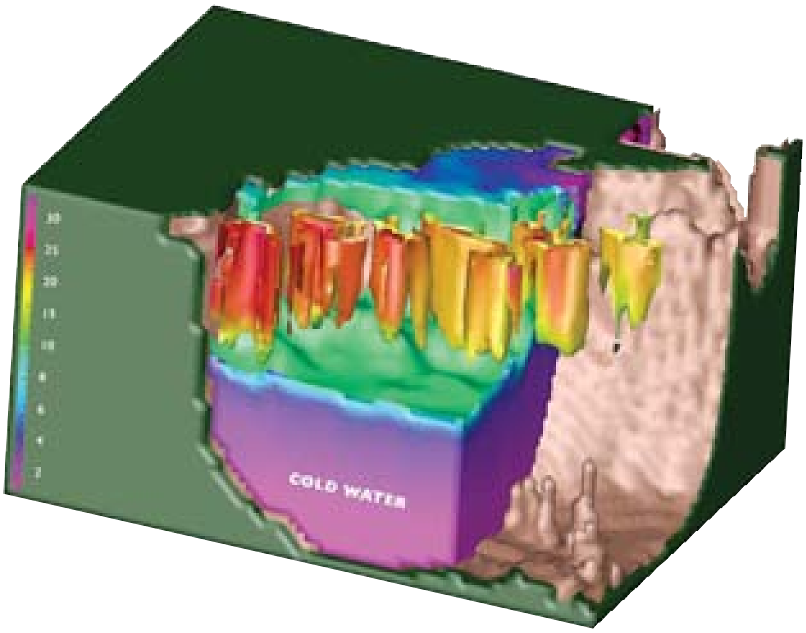
The goals of the science strategy will be achieved only if the data gathered are validated and exploited thoroughly by all research communities concerned. Data exploitation is thus an integral and essential part of the overall science strategy.

To achieve the envisaged scale of impact within the science community and in society at large, a strong European role, innovation, and commitment in the area of data exploitation must be maintained. Specific programmatic actions are needed to ensure that exploitation is actively fostered, facilitated and, where necessary, accelerated.

Data exploitation under the Living Planet Programme should, in terms of its prime objectives, maximise advances and achievements in European scientific understanding of the Earth System, develop new applications that can benefit society and contribute to improved quality of life, and demonstrate new techniques and technologies that can strengthen European industry's competitiveness.

An essential pre-condition is that mission data must be made easily accessible to all user communities concerned - both during the mission lifetime and afterwards (archives). This calls for a user-friendly ground segment that is fully functional, available when each mission is launched, and compatible with the latest information technologies used by scientific communities and laboratories worldwide. This means fast and efficient access to all data. It likewise demands a user-driven approach for mission operations that is adapted to specific mission objectives, and takes full account of the results coming from exploitation as each mission progresses. A transparent mechanism to channel direct feedback from exploitation results into mission planning is needed for the entire lifetime of each mission.

The overall approach to data exploitation should mirror the continuing trend within the scientific community towards multi-disciplinary investigations, integrating observational data from many different sources, making increasing use of the latest data-assimilation techniques, and often performing near-real-time data analysis. The modes of data access and exploitation opportunities offered under the programme need to be adapted for this context. Software toolkits, making pertinent data handling and analysis tools (such as those developed by specialist groups close to each mission) available to the wider user community, along with the basic data products, should be developed and distributed as a general rule.



Three-dimensional representation of eddies in the Gulf Stream system, obtained by the assimilation of satellite data (i.e. sea-surface temperature and sea-level height) into an ocean-circulation model. The plots show warm eddies (defined by a speed of 0.7 m/s) moving above the 10 deg isotherm (in green). The consistent vertical structure of warm eddies associated with sea-level anomalies indicates how the data-assimilation system has propagated the information content from the surface observations into depth.
Credit: Laboratoire des Ecoulements Géophysiques et Industriels, Recherche en océanographie physique, Grenoble

Specific attention should be given to stimulating and facilitating the use of Earth Observation data by research communities that are not specialised in remote sensing. Here the needs of the biological, environmental, health and social sciences disciplines should be considered.

As the time-span of Earth Observation data archives extends from a few years to decades, their value as a scientific time-series increases considerably - especially for global change. In the next decade, the wealth of information currently locked inside the global data archives, complemented with the new data from the Explorers, must be fully exploited and re-analysed on a global scale. Notwithstanding the enormous progress already made in information technologies and Earth Observation ground segments, exploitation on this scale will continue to stretch ground-segment capabilities to their limits for the foreseeable future. The Living Planet Programme should therefore systematically pursue and prioritise such large-scale, global data-exploitation activities, taking advantage of the latest computing technologies such as GRID.

It is expected that the majority of individual scientific investigations making use of data provided from the Living Planet Programme will continue to be directly financed by national research programmes and, to a lesser extent via the European Commission’s Framework Programme. A suite of exploitation activities is needed as part of the Living Planet Programme itself, directly linked to the missions and data, and with strong commitment on the part of the programme and mission authorities.

These activities should directly serve the explicit objectives, strategy and schedule of this Programme, taking particular account of its international scope, innovative character, holistic approach (both science and applications), and the global nature of the issues it addresses. The types of exploitation activities necessary to achieve the overall strategic objectives within the Living Planet Programme include:

- Investigation and development of new observations and associated exploitation techniques to prepare the development of future experimental mission concepts.

- Developing, improving and validating algorithms by exploiting current data in order to achieve better accuracy and performance from existing missions, and thereby meet the needs of the international science community.

- Developing new applications of already approved missions in cases where this can make a significant scientific contribution or demonstrate the operational feasibility of future Earth Observation missions. Previous examples include the development of SAR interferometry starting with the ERS-1 mission, the application of ATSR for global fire detection, and the use of GOME for tropospheric sounding.

- Re-analysing the data acquired since the beginning of the ESA Earth Observation programmes, using improved algorithms, in order to extract global-change fingerprints, or evidence of such.

- Transferring existing experimental exploitation results and methodologies from the research environment into an operational and industrial setting, with a view to developing future potential operational services, or potential precursor applications that could later become operational services.

- Initiating international data-exploitation projects that will ensure European leadership by making a timely and coordinated contribution to major international scientific cooperations, based primarily on data provided via the Living Planet Programme.

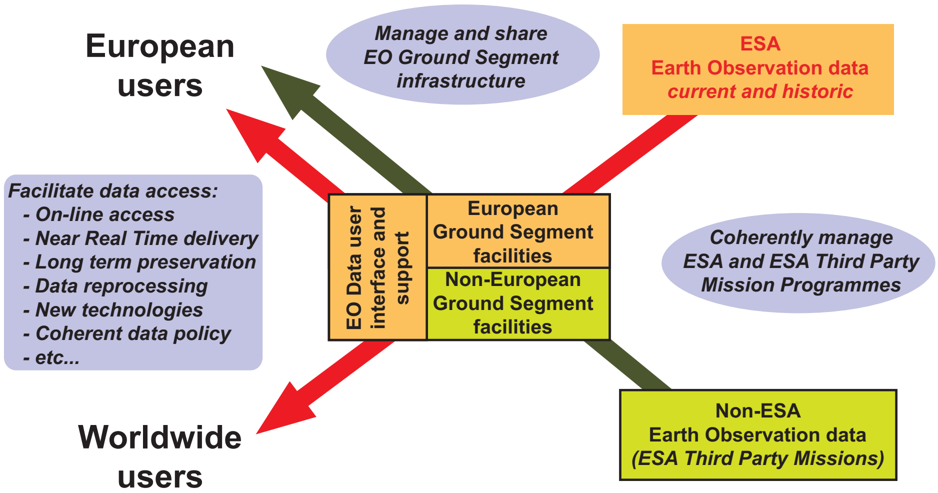
It is vital to ensure that the scientific results and application-related achievements of the Programme are properly communicated to the widest possible audience, via the appropriate channels. Dedicated scientific workshops, symposia, training opportunities and special publications organised under the auspices of the Programme constitute essential platforms for communication within the research community. These are of special value to participants when they are organised around inter-disciplinary themes and facilitate exchanges between different research communities.

It is essential for the success of the science strategy that the technology developments, scientific investigations and applications developments carried out under the Programme be accompanied by a systematic and concerted effort to communicate the achievements to a much wider audience, both within Europe and beyond. This effort should address the general public, political decision makers, schools and universities, all of whom need to be made aware of, kept regularly informed about and kept interested in Europe's achievements in Earth Observation, and have to be convinced of the tangible benefits of investing public funds therein.

6.3 Data and Information Access

The requirements associated with Earth Observation mission operations, ground segments, data and information handling have evolved dramatically over the past five years. Manifested in ESA's day-to-day contacts with the science community and described in the previous chapters, they can be summarised as follows:

- easiest possible data access, continuously adapting to the latest technology



The ESA Earth-Observation Ground Segment.

- coherent access to many - ideally all - sources of EO data and even other geo-data
- fast access, ideally in near-real-time
- long-term access over many (tens of) years
- adaptation of mission, acquisition planning and operations strategies to user demand.

Data volumes
Today's users can handle and process, and therefore request, substantially higher volumes of Earth Observation data than ever before. The current demand for Envisat data is more than twice as high as at launch, and more than four times that foreseen at the start of the satellite's main development phase (C/D). This trend is increasing exponentially. Payload ground segments have to anticipate such an exponential increase in the demand already during the design phase, in order to be able to meet the actual demand at the start of mission operations.

Near-real-time data delivery
Whilst five years ago 'science projects' could be served with data with a delay of weeks, and only 'operational' monitoring projects had to be served with data within hours of its sensing, today the majority of science projects also request data delivery within hours of sensing or ordering. These data are correlated with in-situ measurements, used in NRT modelling and even for tuning other subsequent measurements in near-real-time.

Long-term data preservation
Modelling and long-term trend monitoring have led to a large increase in the demand for time-series and historical data. These data are requested in up-to-date formats, comparable with today's data sources. The challenge therefore lies not only in the archiving of the historical data itself, but even more so in making it accessible on modern media (transcription) and processable through continuous upgrades to processing chains.

Distribution medium
Both the latest and the historical scientific data are requested to a large extent via the standard Internet infrastructure in Europe, North America and Asia. In

The Kiruna ground station, in Sweden, used for Earth-observation data reception and processing.

other areas with smaller ground-link bandwidths, satellite-based Internet access is an option. For really large data volumes, the science centres need specialised hard-disk systems.

User interface

The user interface to the science community increasingly relies on the Internet. This covers the entire chain from data ordering, processing, delivery, feedback and complaint handling, up to the sharing of the scientific results and net-meetings.

This interface can benefit from the ongoing evolution of generic consumer technology, but still needs to be complemented by help-desk, order-handling and mission-planning support, and a skilled interface for dialogue on continuous tailoring and evolving mission operations.

Adaptation of mission planning

While operational and commercial users (except disaster management) wish to see long-term, stable and easily predictable planning of satellite resources, together with little or no change in products and algorithms, the science community expects rapid adaptation to new requirements, fast implementation of new algorithms in routine processing chains, and even fast re-processing of entire archives with these new algorithms. These requirements have to be equally covered in modern ground segments and operations concepts.

New technologies

The scientific community absorbs, adapts and uses the latest computing, information and telecommunications technologies much faster than the operational community. Accordingly, the user-interaction and data-delivery services to scientists have to evolve rapidly to remain compatible with this technology. In addition, innovative support such as the possibility offered to scientists to run their experimental algorithms on the ESA infrastructure, including large data sets and fast processing capabilities, is increasingly appreciated.

Reliability, quality and operability

Science projects require large investments both financially and in terms of manpower. In order to safeguard this investment, they require the same level of reliability as that required by operational projects.

Data delivery has become an infrastructure task from which all users expect the same basic level of response. Confirmed requests have to be satisfied in all cases. For missions operating a priority scheme for the allocation of mission resources, this may have to be amended to improve longer-term scientific planning.

Instrument and product performance are key parameters for the initial selection of the most suitable data set, and for its geo-scientific processing and interpretation. Alongside the introduction of new algorithms, new products and new applications, new parameters may have to be offered routinely. Again, while for operational monitoring such parameters have to assure the 'same' comparable data interpretation, their scientific exploitation calls for a higher degree of innovation and flexibility, by continuously adapting and adding to the offerings of quality and performance parameters.

This evolution in the scientific requirements means that operations and ground segments for scientific missions now have to:

- offer the same level of reliability and operability as former 'operational' missions
- additionally provide a higher degree of flexibility in adjusting and tuning the operations schemes to new projects and technologies, and offer a much closer and intelligent dialogue with the user community.

Science today relies on a multitude of Earth Observation data sources, which can no longer be characterised as science-only missions. Data from public, operational or commercial missions are often indispensable inputs to science projects. A technically simple and coherent, and financially affordable access mechanism needs to be established.

ESA has already started the transition from a 'one-off-defined' ground segment and operations scheme towards the concept of permanent evolution through and beyond every mission lifetime to keep up with the rapidly evolving scientific needs. Only then can the scientific data acquired be exploited to the full.

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